

Test Planning Guide

for

NASA Ames Research Center

Arc Jet Complex and Range Complex

Prepared by
Imelda Terrazas-Salinas
and the staff of the
Thermophysics Facilities Branch
Space Technology Division

NASA Ames Research Center
Moffett Field, CA 94035

Test Planning Guide for NASA Ames Research Center

Arc Jet Complex and Range Complex

APPROVAL SIGNATURES		Date
Author:		
I. Terrazas-Salinas	Signature on File	3/24/99
Review and Approval Team as follows:		
G. Joseph Hartman	Signature on File	3/24/99
Scott G. Eddlemon	Signature on File	3/24/99

REVISION HISTORY			
REV	Description of Change	Author	Effective Date
-	Initial Release	I. Terrazas-Salinas	11/6/98
A	Changed the title of the document Added 2nd preparer Revised footer Corrected typographical errors Expanded sections 1.2, 2.5, 3.0, 3.2, 3.5, 3.6, 4.1.4.1 Added new section 2.6 Added sections 2.7, 4.1.4.6, and 4.2.2.8 Renumbered former section 2.6 as 2.8 Revised sections 2.2.1, 4.1.5.6, 4.2.2, 4.2.2.5, 4.2.2.7.5 Major revision of section 6 Updated Figure 26 Updated table 3 Editorial changes to figures 19 and 22 Editorial changes to sections 2.3, 2.3.1, 4.1.3.1, 4.1.3.2, 4.1.3.3, 4.1.4.3, 4.1.4.5, 4.1.5, 4.1.5.8	I Terrazas-Salinas C. Cornelison	2/8/99

REVISION HISTORY			
REV	Description of Change	Author	Effective Date
B	Added section 1.3.1 Expanded section 3.2 Revised figures 2 and 3 Revised sections 1, 2, 3, and 4.1.4 to conform to standard ARC ISO use of "shall" and to reflect the revisions to figures 2 and 3 Revised section 4.1.4.2 and deleted table 6 Removed figure 28; renumbered figure 29 as 28; Added new figure 29 Expanded section 4.1.4.5 to include slug calorimeters Removed appendices C and D Rearranged headers and footers	I. Terrazas-Salinas	3/24/99
C	Major revision	I. Terrazas-Salinas	4/1/09

Contents

List of Acronyms.....	8
List of Contributors	8
1.0 Introduction.....	9
1.1 Purpose	9
1.2 Scope.....	9
1.3 Location	9
2.0 Administrative Procedures.....	10
2.1 Administrative Authority	10
2.2 Test Approval and Scheduling Procedure	10
2.3 Test Development and Preparation	11
2.4 Test Readiness Review	13
2.5 Test Change Control	13
2.6 Handling of Test Discrepancies During Experiment Occupancy	13
2.7 Post-Test Review	14
2.8 Testing Responsibility.....	14
3.0 Duties and Responsibilities.....	14
3.1 Facility Manager	14
3.2 Test Engineer (Arc Jet Complex).....	14
3.3 Facility Operator	14
3.4 Instrumentation Technician.....	14
3.5 Data System Technician.....	15
3.6 Measurements Engineer (Arc Jet Complex)	15
3.7 Principal Investigator/Experimenter	15
3.8 Optical Engineer (EAST)	15
3.9 Instrumentation Engineer (EAST)	15
3.10 Data Analyst (EAST)	15
3.11 On-site Data Analysis	15
4.0 Facility Description	16
4.1 Arc Jet Complex.....	16
4.2 Range Complex.....	42
5.0 Operating and Safety Procedures.....	67
5.1 Use of the Operating and Safety Manual.....	67
5.2 Emergency Aid and Information.....	67
6.0 Primary Hazards and Safety Features	67
6.1 High Voltage	67
6.2 High-Pressure Gases and Water.....	67
6.3 Vacuum Chambers/Non-breathable Gases	67
6.4 Explosives (Range Complex)	68
6.5 Flammable Gases.....	68
6.6 Personnel Entrapment.....	68
7.0 Emergency Procedures	69
7.1 Direct Response Action	69
7.2 Fire Alarm	69

List of Figures

Figure 1. Map of Ames Research Center	9
Figure 2. Test initiation and approval process	10
Figure 3. Typical test development process	11
Figure 4. Key milestones in the test development process	12
Figure 5. NASA Ames Research Center Arc Jet Complex	16
Figure 6. Test bays of the arc jet complex at Ames Research Center	16
Figure 7. 24×24 in (61×61 cm) panel being tested in the arc jet complex	17
Figure 8. Leading-edge model being tested in the arc jet complex	17
Figure 9. Schematic drawing of the Huels arc heaters used at ARC	18
Figure 10. Schematic drawing of the segmented arc heaters used at ARC	19
Figure 11. Schematic drawing of the semielliptical nozzles at ARC	20
Figure 12. Schematic drawing of a conical nozzle family	21
Figure 13. Schematic representation of the TFD nozzle and test section	21
Figure 14. The segmented arc heater in the AHF	23
Figure 15. Operating envelope of the AHF with 20-MW segmented arc heater	24
Figure 16. Operating envelope of the AHF with 20-MW Huels arc heater	24
Figure 17. 60-MW IHF	25
Figure 18. Operating envelope of the IHF with conical nozzles	26
Figure 19. Operating envelope of the IHF with semielliptical nozzle	26
Figure 20. 20-MW PTF	27
Figure 21. Calorimeter Plate installed in the PTF test cabin	27
Figure 22. Operating envelope of the PTF	27
Figure 23. Operating envelope of the TFD	28
Figure 24. Typical test setup in the AHF, looking upstream	29
Figure 25a. Typical sting adapters for AHF	30
Figure 25b. Typical sting adapters for IHF	30
Figure 26a. Test fixture assembly for PTF and IHF (semielliptical nozzle) (dimensions are in table 4)	31
Figure 26b. Typical model assembly for TPTF	31
Figure 27. Main access door for the IHF	32
Figure 28. Typical test setup in the IHF	32
Figure 29. Examples of typical slug-calorimeter probes	33
Figure 30. Schematic diagram of the five-stage SVS	36
Figure 31. The Hypervelocity Free-Flight Aerodynamic Facility	42
Figure 32. Examples of Aeroballistic Models	43
Figure 33. Photograph of the Ames Vertical Gun Range Facility	47
Figure 34. Sketch of the Ames Vertical Gun Range Facility	47
Figure 35. Typical gun performance	48
Figure 36. Light gas and powder gun performance	48
Figure 37. Air gun performance	48
Figure 38. Photograph of the velocity measuring chamber	49
Figure 39. Impact vacuum tank (exterior view)	49
Figure 40. Impact vacuum tank (interior view)	49
Figure 41. AVGR vacuum system performance	50
Figure 42. Ames standard bucket dimensions	50
Figure 43. AVGR standard vacuum feed-through plate	50
Figure 44. AVGR simplified block diagram	51
Figure 45. Photograph of gun elevation system, beam in horizontal position	52
Figure 46. Scematic diagram of the EAST Facility	56
Figure 47. EAST Facility current collector and arc chamber	57
Figure 48. EAST Facility Driven Tube and components	57
Figure 49. Vacuum Box	59
Figure 50. Optical paths in Vacuum Box	60
Figure 51. Integrating Sphere	61

List of Tables

Table 1. Comparison of the features of the arc heaters at ARC17

Table 2. Operating characteristics of the arc jet facilities at ARC22

Table 3. Minimum lead-length requirements and number of channels supported29

Table 4. Dimensions for IHF and PTF panel test fixtures (drawing shown in fig. 26a)31

Table 5. Available IR-quality viewports33

Table 6. Optical pyrometers provided by ARC34

Table 7. Spectrometers in use at EAST Facility61

List of Acronyms

ARC	Ames Research Center
AVGR	Ames Vertical Gun Range
AHF	Aerodynamic Heating Facility
BEAP	Building Emergency Action Plan
EAST	Electric Arc Shock Tunnel
HFFF	Hypervelocity Free-Flight Facility
HFFAF	Hypervelocity Free-Flight Aerodynamic Facility
HFFGDF	Hypervelocity Free-Flight Gun Development Facility
IHF	Interaction Heating Facility
MSDS	Material Safety Data Sheet
PI	Principal Investigator
PTF	Panel Test Facility
SOP	Standard Operating Procedure
SVS	Steam Vacuum System
TFD	Turbulent Flow Duct
TPS	Thermal Protection System
TRR	Test Readiness Review
TC	Thermocouple

List of Contributors

Wendell Love
John Balboni
Charles Cornelison
Jeff Mach
Andy Gleckman
Jerry Guzman
Jay Grinstead
Ed Schairer
Cesar Acosta
ARC Photographers
Brett Cruden
Mark McGlaughlin

1.0 Introduction

The Thermophysics Facilities Branch of the Space Technology Division at NASA Ames Research Center, Moffett Field, CA, 94035 operates the Arc Jet Complex and the Range Complex for the investigation of atmospheric entry/high-velocity phenomena. The Ames Arc Jet Complex comprises four active arc jet facilities: the Aerodynamic Heating Facility (AHF), the Interaction Heating Facility (IHF), the Panel Test Facility (PTF), and the 2×9 Turbulent Flow Duct Facility (TFD). The Range Complex comprises the Hypervelocity Free-Flight Facility (HFFF), the Ames Vertical Gun Range (AVGR), and the Electric Arc Shock Tunnel (EAST).

1.1 Purpose

This Testing Guide shall serve as an Experimenter's Handbook for all experimenters proposing active investigations using the facilities of the Thermophysics Facilities Branch. Listed are the capabilities of the facilities, interfaces, safety restraints, and operational procedures. With this manual, it is intended that the prospective experimenter can design his/her tests to fit the capabilities of the respective facilities.

1.2 Scope

This document has been prepared to inform all personnel proposing experiments in the Thermophysics Facilities of the details regarding facility capabilities and operational procedures. It is designed to be used in conjunction with the current safety and operational manuals of the respective facilities. Additional procedures are in place to ensure that data/product quality conforms to Agency quality standards.

1.3 Location

The Thermophysics Facilities are located at various locations throughout the Center (see figure 1). The facilities of the Arc Jet Complex are located in Buildings N234 and N238. The Aerodynamic Heating Facility and the Turbulent Flow Duct Facility are located in Building N234; the Panel Test Facility and the Interaction Heating Facility are located in Building N238; Building N234A houses the boiler for the Steam Vacuum System. The telephone number for N234 facilities is (650) 604-5230; that for N238 facilities is (650) 604-5974. The Facility Manager for the Arc Jet Complex is Scott Eddlemon, (650) 604-6075.

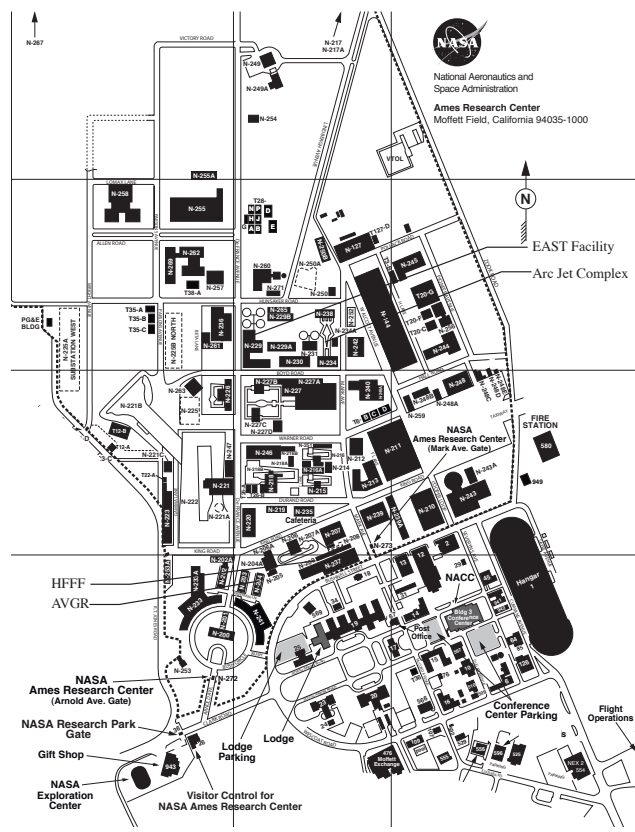
The Range Complex currently comprises three facilities. The first of these facilities is the Hypervelocity Free-Flight Facility. It is composed of the Hypervelocity Free-Flight Aerodynamic Facility (HFFAF) and the Hypervelocity Free-Flight Gun Development Facility (HFFGDF).

Both of these facilities are located in Building N-237. The telephone number is (650) 604-3443.

The second Range Complex facility is the Ames Vertical Gun Range. It is housed in Building N204A. The gun and test chamber are located in Room 102; the control console in Room 101; support machinery is in Room 104; and target fabrication equipment is in Room 101, Building N205. The telephone number is (650) 604-5526.

The third Range Complex facility is the Electric Arc Shock Tunnel Facility. It is housed in building N229. The shock tube is located in Room 157; the capacitor bank/power supply in Room 156; the control console in room 158A; and the laser lab in Room 160. The telephone number is (650) 604-5550.

The Facility Manager for the Range Complex is Charles Cornelison, (650) 604-3443.



1.3.1 Shipping Addresses

Test-related hardware shall be shipped to the attention of the test engineer or the facility manager at the respective test facility, as follows.

For tests in the AHF or TFD, the shipping address is
NASA Ames Research Center
Building 234 Room 112
Moffett Field, CA 94035-1000

For tests in the PTF or IHF, the shipping address is
NASA Ames Research Center
Building 238 Room 103
Moffett Field, CA 94035-1000

For tests in the HFFF, the shipping address is
NASA Ames Research Center
Building 237 Room 150
Moffett Field, CA 94035-1000

For tests in the AVGR, the shipping address is
NASA Ames Research Center
Building 204A Room 104
Moffett Field, CA 94035-1000

For tests in the EAST, the shipping address is
NASA Ames Research Center
Building 229 Room 157
Moffett Field, CA 94035-1000

2.0 Administrative Procedures

2.1 Administrative Authority

The Thermophysics Facilities Branch, in the Space Technology Division, is responsible for the safe and productive operation of these facilities. The Facility Manager enforces the established operating limits of the respective facility and has the authority to judge the acceptance of proposed test programs.

2.2 Test Approval and Scheduling Procedure

It is the policy of the Space Technology Division at NASA Ames Research Center to encourage the maximum utilization of the ARC Thermophysics Facilities within the limits imposed by safety, schedule, funding, and personnel availability.

The Thermophysics Facilities are managed by the Chief of the Thermophysics Facilities Branch. For all of these facilities, with the exception of the AVGR, all tests shall be requested to, and approved by the branch chief. Tests are placed on the facility schedules after receipt of an approved Request for Facility Usage Form. The schedules for the facilities of the Arc Jet Complex are maintained by the Group Leader of the Test Engineering Group; the schedules for the Range Complex are maintained by the facility manager or a branch-approved designee. The

facilities are operated primarily to support government (in particular NASA) aerospace research and developmental testing.

The test initiation and approval process is illustrated in figure 2. The initial steps in the process are informal discussions aimed at determining the feasibility of a concept and, if feasible, which facility is appropriate. These technical discussions occur between ARC engineers and the proposing organization. The process includes examining the test objectives and evaluating the feasibility of accomplishing the objectives. The process continues with a determination of the appropriate facility to carry out the objectives. These activities are accomplished by means of discussions with the test requester, or as appropriate, through a (series of) Test Proposal Meeting(s), as illustrated in figure 2.

For more complex tests, more than one meeting might be required to discuss such points as facility suitability and proposed test approach. The end product of the meeting(s) shall be a completed Request for Facility Usage form, which summarizes the overall test concept, the objectives, and the proposed approach. This form is then submitted for Branch/Division approval as required.

The process then advances to the Test Development stage, described in Section 2.3.

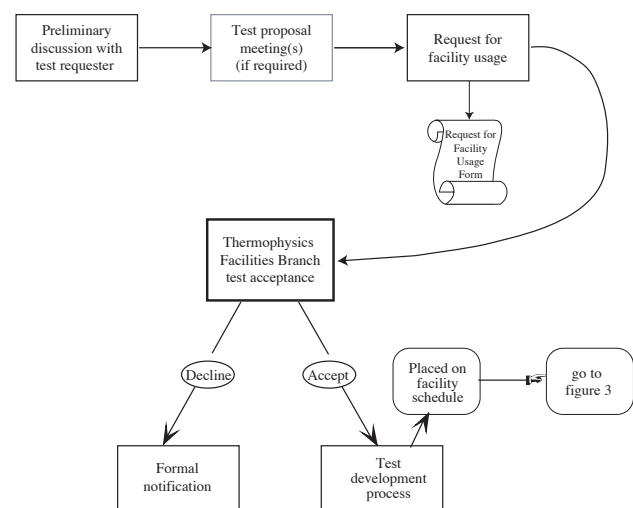


Figure 2. Test initiation and approval process

2.2.1 Vertical Gun

The AVGR is operated as a National Scientific Test Facility. As a national facility, policy guidance is formulated by a Steering Committee, Ames Research Center, Science Coordinator, and NASA Headquarters. Scientific proposals of potential investigators are reviewed through the appropriate Program (Planetary Geology and Geophysics, Exobiology, and Origins Programs) regarding scientific worth. Successful investigators funded by NASA Headquarters are directed to the AVGR Science Coordinator, who provides further practical advice on: preparing for an experimental series; avoiding unnecessary redundancy; and scheduling issues. The AVGR also supports limited exploratory experiments to test a concept or validate an approach for future proposal submissions. The AVGR Science Coordinator is Dr. Peter Schultz. Dr. Schultz can be reached at (401) 863-2417.

2.3 Test Development and Preparation

After a test proposal has been accepted, the test development process begins. This process may take weeks or months, depending on the complexity of the test and the amount of fabrication or facility modification required. A typical test development cycle is shown in figure 3, beginning with approval of the test request and following through with the test and the post-test data analysis. Not all proposed tests require the full development cycle depicted in figure 3. For example, use of existing models and test fixtures would eliminate the model design and fabrication element. On the other hand, complex model development and fabrication may require a rather lengthy review and approval element. Most test programs fall between these two extremes.

A major step in the Test Development sequence is to have a meeting with all research and operations personnel involved in the test. The objectives of this meeting are:

- to begin an interactive exchange between the principal groups;
- to communicate the requirements given in the Request for Facility Usage form;
- to assign tasks to the various groups involved; and
- to explore alternatives where possible.

This meeting provides an opportunity for the technicians in the operations group to talk to the engineers about the test, its objectives, its problems, and its priority. It also allows all personnel to meet each other and to gain an understanding of each other's roles in developing and conducting the test. The meeting is intended to foster a free flow of information, generally through discussions interspersed with questions and answers. The result of this

meeting shall be the formation of the Detailed Test Plan. The moderator for the meeting is the cognizant Thermophysics Facility Manager or his/her designee.

Although the Test Development process details may vary from test to test, the general milestones are essentially the same for all tests. These milestones are shown in figure 4.

2.3.1 Detailed Test Plan

The Detailed Test Plan is a key document that guides all anticipated activity in the test. The plan shall be a complete, stand-alone document that addresses all aspects of the proposed test. The Principal Investigator/experimenter shall be responsible for preparation of the Detailed Test Plan with the assistance of the Test Engineer or Facility Manager, as appropriate, and both shall sign off the complete plan prior to distribution. The signed Detailed Test Plan will be distributed to the Test Readiness Review panel prior to the Test Readiness Review (TRR) meeting. It is preferred that the plan be distributed at least two weeks before the TRR meeting to allow the panel ample time to read the plan. This scenario means that

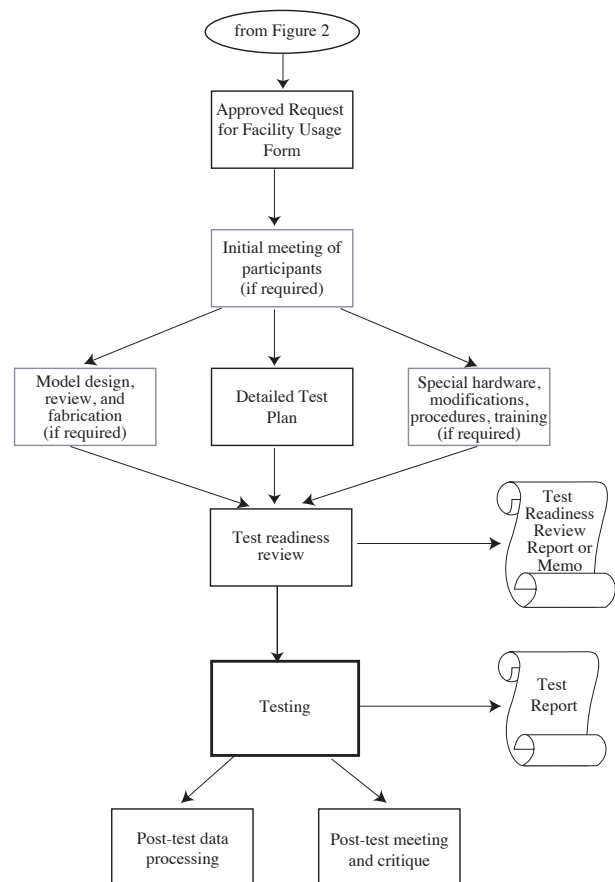


Figure 3. Typical test development process

the Detailed Test Plan should be completed at least four weeks (six weeks is preferred) before the expected start of the test. No systematic effort to prepare for a test will be taken by facility personnel until the Detailed Test Plan is received.

The Detailed Test Plan addresses **ALL** aspects of the test, and includes most or all of the following:

- Overall test objectives and the purpose of the test. State the expected duration of the entry and the facility to be used.
- Approach of the test. State the number of test specimens, describing each type. Describe the proposed run sequence (e.g., calibration runs followed by preliminary screening runs, followed by final evaluation, etc.) and the objective(s) for each run.
- Model description. Describe the test article(s), including the overall size(s), weight(s), physical requirements (e.g., cooling water flow, shrouds, special handling, and storage procedures). Include sketches with dimensions.
- Primary measurements. List the primary measurements to be made, the expected maximum ranges and units, the type of sensor or transducer to be used, whether the sensor would be provided by the customer (in this case, list the the power and interface requirements for the sensor) or by the facility. For example:
 - Surface temperatures Thermocouples
 - Surface pressures Capacitance manometers, diaphragm cells
- Heat flux Water-cooled calorimeter
- Duration in the flow Insertion/retraction schemes
- Model forces Balance system
- Flow velocity Two-dimensional laser
- Time of arrival Interval timers
- Software requirements. Specify the type of data reduction required. Include the desired type of data output (e.g., type and number of graphs, tabular hard copy printouts, electronic data files, etc.).
- Special requirements or hazards. Describe any special or unusual model or facility needs. Describe any hazards associated with handling or testing the model, such as high pressure, toxicity, dust inhalation, etc. Include the material safety data sheets (MSDSs) for all materials used in the test. For arc jet testing, if high-pressure cooling water or high-pressure gas components are included in a model, indicate all hydrostatic test certifications.
- Auxiliary data system/instrumentation. Describe any user-supplied instrumentation and data recording system(s) to be used (not a part of the facility data acquisition system) and their required interfaces.
- List of required personnel and their duties (e.g., facility operator, data technician, photographer, critical systems monitor, etc.).
- Special Standard Operating Procedures (SOPs) that integrate the operation of both the facility and the

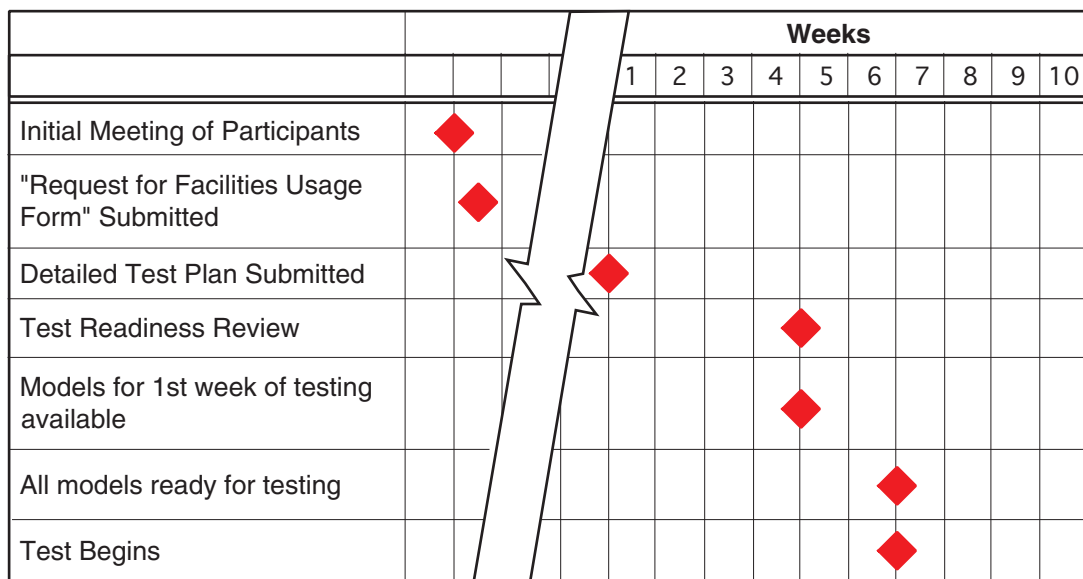


Figure 4. Key milestones in the test development process

model, including pre-run and post-run checklists to ensure that experimenter-supplied equipment is ready to run or properly shut down.

- Emergency procedures for all anticipated emergencies, including shutdown for fire, earthquake, and loss of building power.
- Model operating envelope and constraints, including adjustment for any model effects on established facility limits.
- Communications procedures and protocol, if necessary.
- Pre-run and post-run meeting checklist, if necessary.
- Training plans for the crew to promote test safety and team cohesion, if necessary.
- Security plan, if necessary.
- Inspection plan for post-run (or pre-run) inspection of critical items, if necessary.
- Installation plan for model installation, including rigging and handling as necessary and desired stream coordinates of the model during testing (relative distances from the nozzle exit), if necessary.
- Data recording forms, if necessary.
- Test engineer's forms (and research engineer's) for log sheet, if necessary.
- Test discrepancy report and protocol for handling, logging, and closing out test discrepancies and test change requests.

The Detailed Test Plan shall be thoroughly reviewed at the Test Readiness Review and will become a central part of the Test Readiness Report/Memo. Facility schedules shall be updated as required.

2.4 Test Readiness Review

In order to ensure that all test programs and models are reviewed, critiqued, and approved before the start of testing, there is a standing Branch policy that **ALL** test programs conducted in any Thermophysics Facilities Branch Facility shall have a Test Readiness Review. The TRR shall be scheduled and conducted by the Facility Manager, or approved designee (for tests in the Arc Jet Complex, the TRR shall be scheduled by the test engineer), unless there are unusual hazards or excessive risks involved which require a higher level review (see Chapter 5 of the Ames Safety Manual). A Test Readiness Review is concerned with safety during the conduct of a specific test program. It is intended to bring together all the personnel directly involved in the test to ascertain that problem areas have been resolved, that all procedures are clear and

complete, that all hardware is properly designed, and that the operating crews are trained and know what to expect from the test. The review also assures that the instrumentation technicians are aware of their role and that proper instrumentation is available, all operating procedures are within the facility's normal operating envelope, emergency procedures are adequate, all possible hazards are discussed and evaluated, the test plan is reasonable and complete and will accomplish the test objectives. Above all, the review shall ensure that adequate safety measures have been taken to assure the safety of the personnel, facility, and test hardware.

An approved TRR only applies to the test plan, models, and hardware discussed. Any change in model configuration, hardware, or test plan that, in the opinion of the Facility Manager, significantly alters the basis for the original approval will require a new review. Any models, targets, or support fixture not previously reviewed will require an independent review. A test shall be approved for facility operation only after the TRR has been completed and a summary memo or report has been signed by the Branch Chief and/or Facility Manager.

2.5 Test Change Control

It is the policy of the Branch that all test and model activity shall be conducted with Test Change Control as an integral part of the activity. Test-related changes will be the responsibility of the Test Engineer and/or the Principal Investigator. At a minimum, these changes shall be documented in the Test Engineer's Log Book, and/or indicated as "red-line" changes to the test plan. The red-line changes shall be initialed by the Test Engineer and/or the Principal Investigator. The Facility Manager, or his/her designee, shall review and approve all Test Change Requests unless there are unusual hazards or excessive risks involved which require a higher level review. Depending on the nature of the requested change, testing may be halted until the change is approved. Changes to the test sequence are excluded from this requirement.

2.6 Handling of Test Discrepancies During Experiment Occupancy

Discrepancies that arise during the course of a test program shall be handled at the discretion of the Facility Manager or his/her designee. He/She shall evaluate the impact of the discrepancy as it relates to the objectives of the test program and to possible safety-related risks. Discrepancies and their resolution shall be logged in a Test Discrepancy Log (Arc Jet Complex) or on the test data sheet (Range Complex). As appropriate, the Centerwide Nonconformance Report/Deviation Waiver process shall be used.

2.7 Post-Test Review

It is Branch policy to conduct post-test review meetings with customers of the Thermophysics Facilities Branch. The purpose of this meeting is to discuss test-related highlights, problems, lessons-learned, and recommendations. All test discrepancies, process change recommendations, and suggestions will be discussed. Notes from this meeting will be noted in the Test Engineer's Log Book or by the Principal Investigator. At the discretion of the Test Engineer/Principal Investigator, issues which warrant management involvement shall be brought to the attention of the Branch Management.

Each customer shall be asked to provide a Post Test User Review Report/memo. This report/memo will provide a written critique to the Branch in order that the Branch may improve its processes.

2.8 Testing Responsibility

The responsibility of facility operation, safety, maintenance, and raw data acquisition shall be that of the personnel of the Thermophysics Facilities Branch. The Facility Manager shall be responsible for all aspects of the facility operation, including, for the Range Complex, the integrity of the launch package, the gun powder charge, and pump tube pressure. He/She shall be responsible for assuring that all operating parameters selected for a particular test are within the safe operating limits of the equipment. Assistance may be given by the facility Branch personnel in obtaining test gases other than air, however, the specifications shall be provided by the experimenter/principal investigator. Data reduction/analysis relating to facility operation parameters shall be the responsibility of the operating personnel. These data include items such as projectile velocity, size, weight, as appropriate, and other standard data such as pressure, temperature, etc. in the test chambers. Data reduction/analysis regarding model/test article performance shall be the sole responsibility of the Principal Investigator.

The process through which all tests shall proceed, from test approval to post-operation activities, has been outlined in Section 2.3. The Thermophysics Facilities Branch shall be responsible for managing this process and for safely conducting the tests. Emphasis shall be placed on those steps that ensure that all safety requirements are met. Not all test preparations are the same because of differences in facilities and in test requirements. However, all tests shall be subjected to similar milestones and undergo the standard review and approval process before testing begins. These steps generally include: (1) initiation of the Request for Facility Usage form and its acceptance by the Thermophysics Facilities Branch; (2) development of test model hardware, test conditions, interfaces, procedures, and the Detailed Test Plan; (3) fulfilling the

requirements of the Test Readiness Review; and, (4) the test operations and data distribution.

3.0 Duties and Responsibilities

The Branch Chief, Thermophysics Facilities Branch, is responsible for all aspects of the operation, safety procedures, and maintenance of the facilities. He/she delegates some of the operational responsibility and operational duties as detailed below. The day-to-day operation of the Facilities is under the technical guidance of the respective Facility Manager. All branch personnel follow Agency quality policies and procedures as set forth by Center, Directorate, Division, and Branch Management in order to ensure that the data/product delivered by the Branch meets or exceeds the customer's requirements.

3.1 Facility Manager

The Facility Manager is responsible for the technical, efficient, and safe utilization of the facilities within the Thermophysics Facilities Branch. He/she enforces the established operating limits of his/her respective facilities and has the authority to judge the acceptance of all proposed tests. He/she conducts a Test Readiness Review with the Principal Investigator/experimenter and the operating personnel for ALL proposed tests. He/she maintains certification for all operating personnel and schedules retraining when required.

3.2 Test Engineer (Arc Jet Complex)

The Test engineer is responsible for the conduct of the test program and coordinates all aspects of the tests once testing has begun. He/She is responsible for maintaining the Test Discrepancy Log and for working post-test with the customer to resolve any discrepancies that arise during the test occupancy in the facilities.

The Group Leader of the Test Engineering Group maintains the schedules for the facilities of the Arc Jet Complex and interfaces with the Principal Investigators during the test planning phase of a test program.

3.3 Facility Operator

The Facility Operator is responsible for operating the facility according to the test program. He/she has been certified to operate the facility by the Facility Manager. His/her duties include operation using documented procedures and checklists, and making entries in the facility operation log book. He/she is responsible for ensuring that the facility is operational.

3.4 Instrumentation Technician

The Instrumentation Technician is responsible for ensuring proper functioning of the instrumentation required for the tests and for connecting these to the data acquisition system, as appropriate.

3.5 Data System Technician

The Data System Technician has the primary duty to support data acquisition activities and to reduce the recorded data as required by the test program. Additionally, he/she is responsible for archiving the data and performing periodic backups of the data acquisition system.

3.6 Measurements Engineer (Arc Jet Complex)

The Measurements Engineer is responsible for Engineering oversight of the Instrumentation and Data Acquisition Systems. He/She is responsible for verifying that changes to the Arc Jet Data System configuration are done correctly. His/her duties also include modification of the Arc Jet Data System to integrate new instrumentation or calculations.

3.7 Principal Investigator/Experimenter

NASA personnel provide normal levels of test support, including test development, model preparation and installation, instrumentation checkout, and data reduction. Users (also referred to as Principal Investigators or Experimenters) of these facilities are expected to provide all hardware, support equipment, and test personnel specific to a given test. Users are responsible for funding any facility modification costs and for any nonstandard operational costs that are required to properly meet the objectives of the requested test program. In certain instances, the user may be required to fund all operational costs associated with a test. Specific details on the policies for funding test costs are addressed by Branch and Division Management.

In the Arc Jet Complex, the Principal Investigator interfaces with the test engineer regarding any aspect of his/her test.

3.8 Optical Engineer (EAST)

The optical engineer is responsible for maintaining the optical components of the system in working order, under calibration and in alignment. The optical engineer reports

to the facility manager, and interfaces with the PI to the extent necessary for the PI to determine how optical issues impact the technical quality of the data. The optical engineer is a part-time position in the facility. The individual serving in the role of optical engineer may perform other duties in the facility.

3.9 Instrumentation Engineer (EAST)

The instrumentation engineer is responsible for overseeing operation of all instrumentation on the shock tube other than optics. This includes pressure sensors, data acquisition system, control system and other electrical subsystems. The instrumentation engineer reports to the facility manager and interfaces with the PI as needed for assessing quality of data and its interpretation.

3.10 Data Analyst (EAST)

The data analyst performs post-processing on collected data and synthesizes collected data into a useful format for the PI. This includes analysis of shock velocity, applying calibration factors to spectroscopic data and producing automation routines. The analyst reports to the PI.

3.11 On-site Data Analysis

The Thermophysics Facilities Branch does not support on-site data analysis. Investigators requiring immediate analysis of their test data are urged to provide their own data analysis equipment (lap top computer with the appropriate data analysis software). If a network connection is required (e.g. for internet access or e-mail access) the investigator should ensure that his/her equipment has an ethernet port. In this case, the PI must request a network connection in his/her test plan and will be required to have his/her computer scanned by ARC IT Security prior to connecting to the ARC network. Immediate transfer of preliminary electronic test data to the investigator, if required, will be done via single-write CDs.

4.0 Facility Description

4.1 Arc Jet Complex

The Ames Research Center currently operates a variety of arc-heated facilities within the Arc Jet Complex. These facilities are used to generate flow environments that simulate the aerothermal environment that an object experiences when traversing the atmosphere of a planet. They are used primarily to test heat shield materials and thermal protection system (TPS) components for planetary entry vehicles, planetary probes, and hypersonic flight vehicles, although other investigative studies are performed in some of these facilities. In the arc jet facilities, TPS components are exposed to the aerothermodynamic heating conditions that they will encounter during high-speed flight.

The Arc Jet Complex (fig. 5) at ARC has nine available test bays located in two separate laboratory buildings. Figure 6 shows a schematic representation of the location of these test bays. Presently, four bays contain operational arc jet units of differing configurations. The arc jet facilities are serviced by common facility support equipment, including two dc power supplies, a steam-ejector vacuum system, a de-ionized water cooling system, high-pressure gas systems, data acquisition system, and other auxiliary systems. The magnitude and capacity of these support systems is what primarily distinguishes the ARC Arc Jet Complex as unique in the aerospace testing world. In particular, the large dc power supply can deliver 75 MW for 30 minutes. High-power capability, in combination with the high-volume steam-ejector vacuum system, yields a unique suite of facilities that simulate high-altitude atmospheric flight on relatively large test objects.

The arc heater units were designed at NASA Ames and

are of both the segmented design and the Huels-type design. These arc heaters, combined with a variety of conical, semielliptical, and two-dimensional nozzles, offer wide versatility for testing both large, flat-surface test objects (fig. 7) and stagnation-flow models that are fully immersed in the test stream (fig. 8).

4.1.1 Arc Heaters

The arc heaters are key features of the arc jet complex; they contain three fundamental elements: a cylindrical volume for containment of the arc discharge (or arc), a pair of electrodes (anode and cathode), and a nozzle. The desired test gas is injected into the cylindrical section and an arc discharge passes between the electrodes, heating the gas to a high temperature. The plasma then flows through a converging/diverging nozzle, producing the simulated atmospheric-entry heating environment. The design of the cylindrical confining device must simultaneously satisfy numerous difficult requirements. The confining device must incrementally withstand the voltage potential between the electrodes, which can total more than 20,000 volts (V). It must be highly water cooled in order to contain the plasma, which can reach temperatures in excess of 15,000 °F (8,300 °C). It must serve as a pressure-containment vessel; as such, all seals and joints must be adequate to prevent leakage at conditions ranging from vacuum up to pressure levels of several hundred pounds per square inch (psi). It must have adequate mechanical strength for the loads involved. Finally, the materials used must have the proper electrical, thermal, mechanical, and chemical properties to meet all these requirements. Development of increasingly higher-power arc heaters has been conducted at ARC over more than 30 years.

Two basic types of arc heaters are used at ARC. The arc jet facilities are driven by either a segmented (also called



Figure 5. NASA Ames Research Center Arc Jet Complex

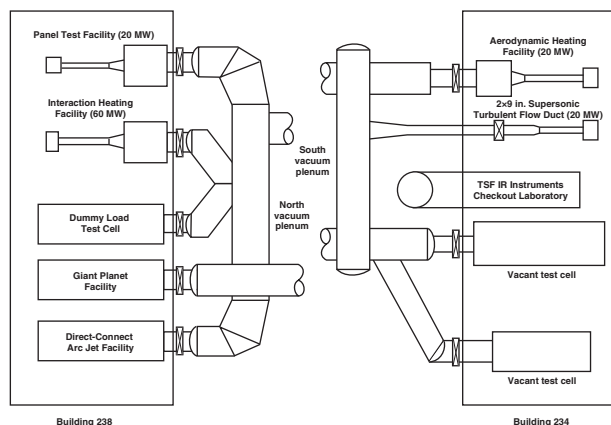


Figure 6. Test bays of the arc jet complex at Ames Research Center



Figure 7. 24×24 in (61×61 cm) panel being tested in the arc jet complex

“constricted”) arc heater or by a Huels-type (also called “Linde-type” and “vortex-stabilized”) arc heater. These two basic arc heater types, which have quite different operating characteristics, have proved themselves over the years and are used extensively for a wide variety of testing. Segmented arc heaters produce lower contamination levels in the flow stream compared to Huels-type arc heaters. The stream contamination produced from the electrode material in a segmented arc heater is less than 10 parts per million (ppm) of the mass flow; in a Huels type, it is an order of magnitude higher. The salient features of these two types of arc heaters and the major differences between the two designs are described in the next section. Table 1 compares the features of the two arc heater types.

Table 1. Comparison of the features of the arc heaters at ARC

Feature	Segmented arc heater	Huels arc heater
Enthalpy	High (to 20,000 Btu/lb _m [46,520 kJ/kg])	Low (to 4,000 Btu/lb _m [9,304 kJ/kg])
Pressure	Low (to 10 atm [980 kPa])	High (to 100 atm [9,800 kPa])
Flow contamination	Low (< 10 ppm)	High (> 10 ppm)
Arc column	Fixed length	Natural (variable) length
Repeatability	Repeatable performance	Inconsistent performance
Hardware	Complex	Simple
Maintenance	Difficult	Relatively easy

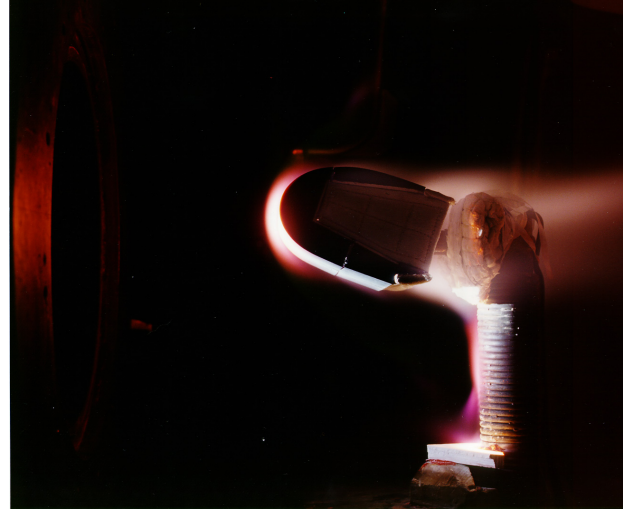


Figure 8. Leading-edge model being tested in the arc jet complex

4.1.1.1 Huels Arc Heater

Hardware– The Huels arc heater is a relatively simple unit containing few components. The arc heater comprises two water-cooled cylindrical electrodes, separated by an enlarged cylindrical swirl chamber and a single large insulator, which withstands the entire voltage potential between electrodes. (See fig. 9.) The downstream electrode is electrically grounded by physical contact with the vacuum system piping.

Operation– During operation, dry air is introduced tangentially into the swirl chamber; the strong vortex thus formed is largely responsible for stabilizing the arc discharge. A magnetic field coil surrounding the upstream electrode rotates the arc attachment point. This rotation reduces electrode erosion and fixes the axial attachment location of the arc. The arc is driven into the upstream electrode by the vortex and is restrained from attaching to the closed end of the electrode by the magnetic field of the coil. In some cases a similar field coil is used on the downstream electrode to prevent the arc from blowing through the nozzle.

The operating characteristics of a Huels arc heater are somewhat variable. The arc discharges in a somewhat erratic mode, and does not necessarily locate on the anode and cathode in a repeatable fashion from one run to another. The discharge voltage is a function of the length of the arc, which is governed by two competing factors:

- The arc discharge seeking a free path of least resistance, and
- The cold gas near the walls from the vortex flow preventing conduction to the walls.

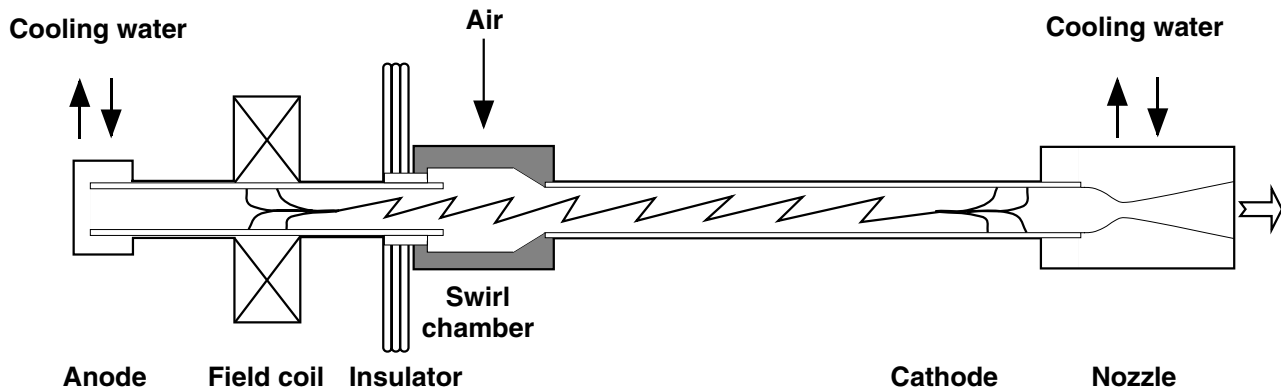


Figure 9. Schematic drawing of the Huels arc heaters used at ARC

Because the arc seeks an equilibrium between these two competing parameters, it is said to seek its “natural” operating length, in contrast with the fixed-arc-length characteristic of the constricted arc heater.

The Huels arc heater can be operated at high pressures (over 100 atm [10MPa]), but it produces plasmas at relatively low enthalpies (1,500 to 4,000 Btu/lb_m [3.5 to 9.3 MJ/kg]) because of the inherently low current density of the vortex-stabilized arc. The simplicity of the unit, however, allows for relatively easy maintenance and short turnaround times during testing.

The basic Huels arc heater geometry as operated by ARC is shown in figure 9. This arc heater has been used with a variety of nozzles in different test bays and is available in three sizes: 5-, 20-, and 100-MW units. Each of the units is available with various downstream electrode lengths, allowing the operator to select a tube length that will best match the expected “natural” arc length. Current designs are for a Huels arc heater operating at a power level of 100 MW with pressure capabilities to 100 atm (10 MPa), which requires gas flow rates of 15 lb_m/sec (6.8 kg/sec) or more. Power levels as high as 55 MW have been demonstrated in a Huels arc heater at ARC.

4.1.1.2 Segmented Arc Heaters

Hardware— The segmented arc heaters are relatively complex units with many components and critical assembly alignments. (See fig. 10.) Therefore, the segmented arc heater requires more frequent inspection and maintenance than the Huels-type arc heater. The primary components of the segmented arc heater are the electrodes (anode and cathode) and the constrictor tube. The entire arc heater, including both electrodes, is electrically isolated from the ground.

The constrictor tube, or column, consists of a few hundred individually water-cooled copper disks, or segments,

clamped together to form a cylinder. Electrically isolated from the others, each disk is supplied with water cooling. (The incremental voltage potential between adjacent disks in the constricted arc heater is relatively low, usually less than 50 volts, in contrast to the Huels-type arc heater in which a single insulator stands between anode and cathode potentials of up to 33 kV.) The disk segments and the associated insulators and seals are packaged into modules of 30 disks for ease of assembly and testing.

The length of the constrictor tube is tailored to the desired arc heater performance, with proper consideration for the mass flow, voltage, and arc current. The arc length is fixed by the length of the constrictor tube, in contrast to the “natural” arc length of the Huels arc heater. As a result, the segmented arc heater operates in a relatively stable fashion, with excellent repeatability.

The anode and cathode of the segmented heaters consist of multiple-ring electrodes contained in assemblies called electrode packages. Each electrode package consists of individual electrode, spacing, and transition rings. Each electrode ring is electrically isolated from the others and is individually ballasted. The diameter of the copper electrode rings is larger than that of the disks in the constrictor column, thus forming a plenum. Each electrode ring contains an internal magnetic spin coil in series with the arc current. The coil produces a magnetic field that acts to rotate the arc attachment point around the inside of the electrode ring, thus reducing erosion from the highly concentrated arc foot.

Both of the power supplies that service the Arc Jet Complex are current-controlled; thus the total arc current is specified at all times. An electrode package is assembled with a sufficient number of electrode rings to handle the anticipated operating current. By adjusting the variable ballast resistors, the parallel electrode rings within a package can be forced to share current approximately equally.

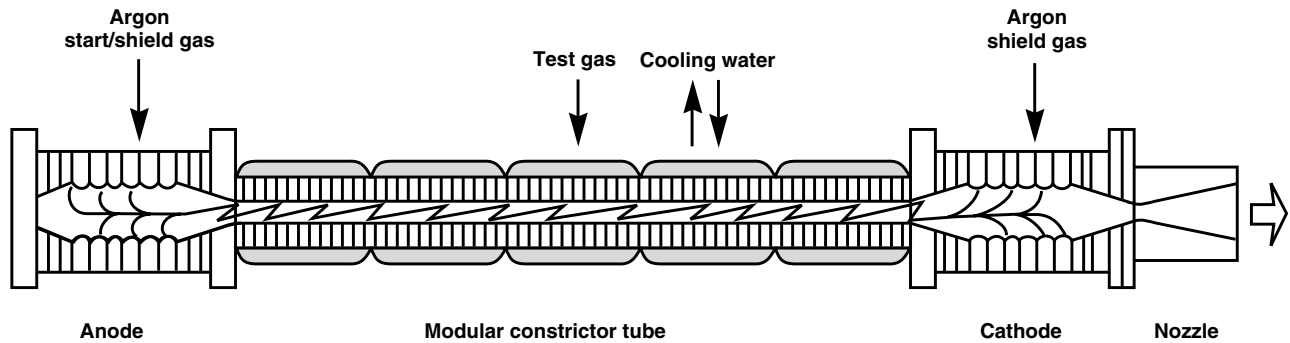


Figure 10. Schematic drawing of the segmented arc heaters used at ARC

A small amount of argon gas is injected between each electrode ring to ensure that sufficient ionization is maintained near the surface of the electrodes. Because the total arc current is divided between multiple electrodes, each of the multiple arc attachment points produces a lower thermal load to the electrode wall compared to the single attachment point in a Huels arc heater. The total amount of argon in the test stream is controlled by operator inputs.

Operation— During operation, the gas (usually air) is introduced between adjacent disks along the entire length of the constrictor tube. The mass flow distribution of test gas along the constrictor tube and the type of gas can be changed to tailor the performance of the arc heater. For instance, a small flow of argon is bled in between disks near the anode, or upstream electrode, to prevent intersegment arcing.

The segmented arc heater provides a wider range of enthalpy levels and a more stable and repeatable test condition than the Huels arc heater. The segmented arc heater can produce relatively high enthalpy levels (5,000 to 20,000 Btu/lb_m [10 to 50 MJ/kg] in air) at relatively low pressures (1 to 10 atm [100 to 1,000 kPa]). It can also be operated at high pressures (above 100 atm [10 MPa]), but the design problems associated with high-pressure operation are considerable because of the complexity of the segmented construction. ARC has elected to restrict operations to the lower pressure range; thus all the segmented arc heaters at ARC operate at relatively low pressures.

The basic geometry of the segmented arc heater as operated at ARC is shown in figure 10. This type of arc heater is coupled to a variety of nozzles (of both semielliptical and circular cross section) in different test bays; it is available in two sizes: a 6 cm (2.4 in) bore and an 8 cm (3 in) bore constrictor tube. The arc heaters of both sizes use the same electrode package components and are assem-

bled with four to eight electrode rings in the package. The number of electrode rings in the package is determined by the level of arc current that is required.

Another configuration of the 6 cm (2.4 in) bore segmented arc heater has operated at power levels up to 80 MW using hydrogen/helium mixtures as the test gas. This arc heater utilizes carbon-rod cathode electrodes located downstream of the nozzle exit so that the arc discharge passes through the nozzle. This configuration was selected to ensure the maximum possible energy transfer to the gas, thereby attaining the extremely high enthalpy levels for simulation of entry into the atmosphere of the giant planets. A small-exit-diameter nozzle was used for testing samples in an open jet at extremely high heating rates.

4.1.2 Nozzles

A supersonic nozzle is coupled to the downstream end of the arc heater to produce the desired flow environment. The ARC arc jet facilities customarily use nozzles of two cross-sectional geometries: asymmetric semielliptical and axisymmetric conical nozzles. The nozzles are fully water cooled to allow for continuous operation. With the exception of the 2 × 9 Supersonic Turbulent Flow Duct, the nozzles operate with an open jet test section.

4.1.2.1 Semielliptical Nozzles

The semielliptical nozzles have an asymmetric cross section that is one-half of an ellipse. The flat, bottom portion of the nozzle forms the major axis of the elliptical section (fig. 11). A flat-panel test article is mounted flush to the bottom, flat surface of the nozzle in a semiopen jet at the nozzle exit.

The semielliptical nozzles were developed at ARC to test large, flat surfaces in high-temperature boundary layer flows (e.g., development of the Space Shuttle heat shield tiles). All nozzles have a circular subsonic inlet transitioning to a semielliptical throat, which expands

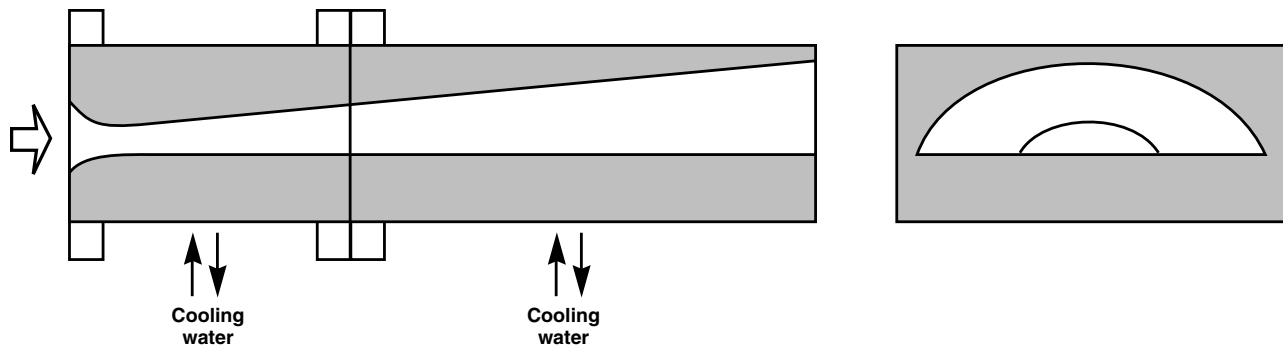


Figure 11. Schematic drawing of the semielliptical nozzles at ARC

conically to the test section. The semielliptical cross section produces a relatively uniform heat flux and surface pressure distribution over a large, flat test article. Choice of this configuration was based on the results of a nozzle development program in a pilot facility that showed that rectangular, two-dimensional nozzles with high aspect ratio produce unacceptable nonuniformity at the test section. About 75 percent of the nozzle exit width is usable in a semielliptical nozzle. At the nozzle exit, the transverse variation in heat transfer rate and surface pressure is less than 15 percent. The magnitude of the transverse and streamwise variation is shown in Appendices A and B. Variations in streamwise heating and pressure distribution are greater at higher inclination angles and higher arc current levels.

The 20 MW PTF has two semielliptical nozzles available. They include:

- a nozzle of 17 in (43 cm) exit width to provide aerodynamic heating onto a 12 × 12 inch (30 × 30 cm) flat panel; and
- a nozzle of 6.7 in (17 cm) exit width to provide aerodynamic heating onto a 4 × 4 inch (10 × 10 cm) flat panel.

The 60 MW IHF has one semielliptical nozzle available. It is a nozzle of 32 in (81 cm) exit width and can test flat panels up to 24 × 24 inches (61 × 61 cm) in size.

The larger of the semi-elliptical nozzles for both PTF and IHF operate at an approximate Mach number of 4.5 and are fitted with an uncooled, high-temperature plate over the final 20 percent of the length of the flat portion of the nozzle (upstream of the test panel). This boundary layer conditioner plate, of length greater than 10 times the thermal boundary layer thickness, tailors the boundary layer of the flow before it reaches the test article so that it better simulates the boundary layer flow experienced on the windward side of an atmospheric entry vehicle. The simulated length Reynolds number is approximately 1×10^6 , based on boundary layer growth beginning at the

throat and continuing to the nozzle exit.

The smaller PTF semi-elliptical nozzle produces flows at approximately Mach 2.2. Compared with the other semielliptical nozzles, it can simulate higher heating rate, higher pressure, and higher shear. Installing this nozzle requires adding the extended test chamber onto the PTF. All of the Ames semielliptical nozzles allow the test panel to be inclined at positive and negative angle of attack with respect to the flow stream.

4.1.2.2 Axisymmetric Nozzles

The arc jet complex uses a variety of axisymmetric conical nozzles; most are not contoured. This conical design was chosen because:

- design and fabrication are relatively simple;
- mating sections of conical nozzles offers great flexibility in varying the area ratio;
- the conical nozzles are not restricted to a fixed Mach number, as are contoured nozzles; and
- ARC has had vast experience in developing heat shield materials using conical nozzles in the presence of high-enthalpy reacting flows.

Nozzle throat sections are fabricated using water-cooled copper. Expander sections are either aluminum with deep-drilled water cooling passages or water-jacketed steel.

The arc jet complex has two conical nozzle systems:

- 20-MW Aerodynamic Heating Facility
 - Throat diameters of 1.0, 1.5, and 2.0 in (2.5, 3.8, and 5.1 cm)
 - Exit diameters of 7, 12, 18, 24, 30, and 36 in (18, 30, 46, 61, 76, 91 cm)
- 60-MW Interaction Heating Facility
 - Throat diameter, 2.375 in (6.033 cm)

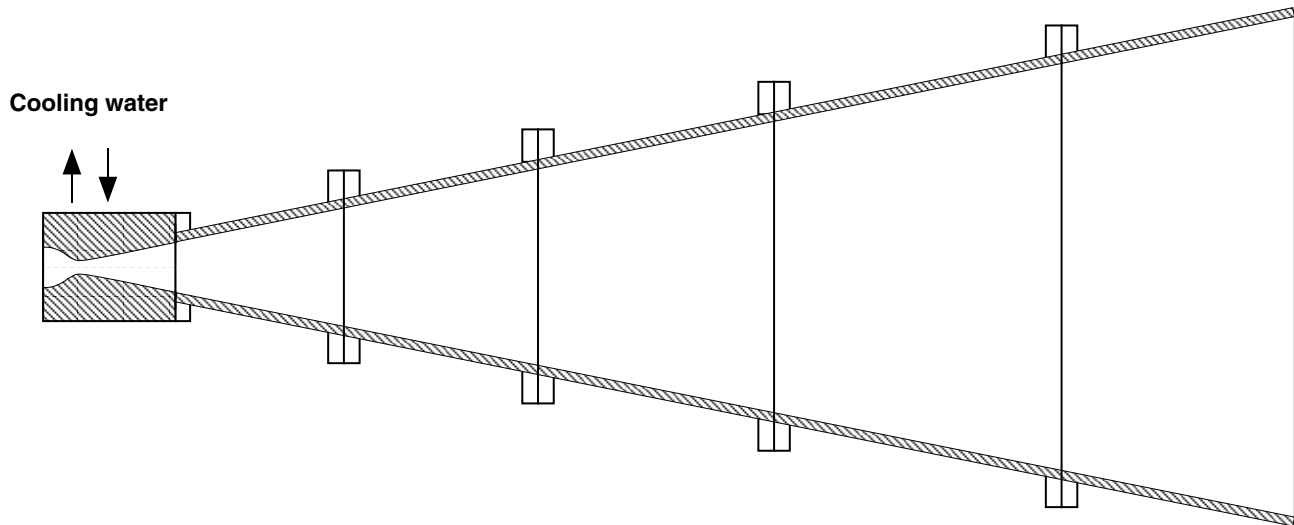


Figure 12. Schematic drawing of a conical nozzle family

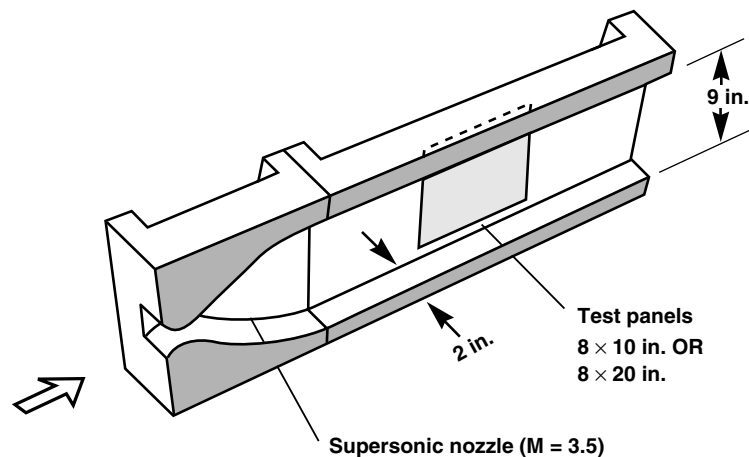


Figure 13. Schematic representation of the TFD nozzle and test section

- Exit diameters of 6, 8, 13, 21, 30, and 41 in (15, 20, 33, 53, 76, 104 cm)

In each facility, the location of the nozzle exit plane remains fixed when the number of frustum sections in the nozzle is changed. The arc heater assemblies are mounted on wheeled carriages to make up the difference in axial location for various nozzle configurations. Figure 12 shows a schematic drawing of a typical conical nozzle family.

4.1.2.3 Other Nozzles

Other special-purpose nozzles are available for use with specific arc heaters. They are described in the following paragraphs.

2 × 9 TFD Nozzle– The TFD is driven by a 20-MW Huels arc heater to produce turbulent flow over the surface of a wall-mounted panel in the constant-area section of a duct. The subsonic section of the nozzle is circular, transitioning to a rectangular throat section of dimensions 1.128 × 1.600 in (2.865 × 4.064 cm). One wall expands to the 9 in (20 cm) dimension with a slight boundary layer correction divergence (less than 0.5°). The other wall is contoured to complete the expansion. The TFD nozzle is made of copper, with internal passages for water cooling. Static pressure ports and heat-flux sensor ports are spaced along the centerline from a point 3 1/16 in (7.50 cm) from the minimum section extending to the nozzle exit. Figure 13 shows a sectional view of the 2- by 9-inch duct nozzle and test section.

Table 2. Operating characteristics of the arc jet facilities at ARC

	Aerodynamic Heating Facility		2×9 Turbulent Flow Duct	Panel Test Facility	Interaction Heating Facility	
Nozzle Configuration	Conical		2-Dimensional	Semi-elliptic	Semi-elliptic	Conical
Gas	Air, Nitrogen		Air, Nitrogen	Air	Air	Air
Input Power, MW	20		20	20	75	75
Type of test Article	Stagnation	Wedge	Flat Plate	Wedge	Wedge	Stagnation Wedge
Nozzle Exit Dimension, in	7, 12, 18, 24, 30, 36 dia.		2 × 9	4 × 17 1.5 × 6.7	8 × 32	6, 8, 13, 21, 30, 41 dia.
	18, 33, 46, 61, 76, 91 dia.		5 × 23	10 × 43 3.8 × 17	20 × 81	15, 20, 33, 53, 76, 104 dia.
Mach Number	4 – 12		3.5	5.5	5.5	< 7.5
Sample Size, in	8 dia.	26 × 26	8 × 10 8 × 20	14 × 14	24 × 24	18 dia.
	20 dia.	66 × 66	20 × 25 20 × 51	35 × 35	61 × 61	46 dia.
Bulk Enthalpy, Btu/lb_m	5000 – 14,000		1500 – 4000	2,000 – 14,000	3,000 – 20,000	
	10 – 32		3.5 – 9.5	4.6 – 32	7 – 46	
Surface Pressure, atm	0.005 – 0.125	0.001	0.02 – 0.15	0.0005 – 0.05	0.0001 – 0.02	0.010 – 1.2
Convective Heating Rate, Btu/ft²sec	20 – 225	0.05 – 22	2 – 60	0.5 – 75	0.5 – 45	50 – 660
	23 – 255	0.06 – 25	2 – 68	0.6 – 85	0.6 – 51	56 – 749
Radiative Heating Rate, Btu/ft²sec	0		0	0	0 – 5	0 – 20
	0		0	0	0 – 6	0 – 23

4.1.3 Description of the Arc Jet Test Facilities

There are currently four active facilities in the ARC Arc Jet Complex. The features of these facilities are described in this section and summarized in table 2.

4.1.3.1 Aerodynamic Heating Facility

The AHF is a highly flexible arc jet facility that operates with either of two 20-MW arc heaters and a family of conical nozzles. The segmented arc heater, shown in figure 14, operates at pressures from 1 to 10 atm (100 to 1,000 kPa) (reservoir pressure) and enthalpy levels from 5000 to 14,000 Btu/lb_m (11 to 33 MJ/kg) (air). The Huels arc heater operates at pressures from 1 to 40 atm (100 to 4000 kPa) and enthalpy levels from 1500 to 4000 Btu/lb_m (3.5 to 9.3 MJ/kg) (air). Most of the testing in the AHF is done using the segmented arc heater because of its high enthalpy performance, low stream contamina-

tion, and long history of repeatable operation. Alternate test gases are nitrogen and argon. Either arc heater can be coupled with a family of 8°-half-angle conical nozzles of exit diameters of 12, 18, 24, 30, or 36 in (30, 46, 61, 76, 91 cm) (figure 12). Each nozzle has an interchangeable throat of diameters of 1.0, 1.5, or 2.0 in (2.5, 3.8, and 5.1 cm). The nozzle discharges into a 8- × 8- × 8-ft (2 × 2 × 2 m) walk-in test cabin. Flow in the cabin is collected by the 60 in (150 cm)-diameter diffuser before being pumped through a heat exchanger into the steam-ejector vacuum system. Static pressure in the cabin ranges from 0.1 to 10 torr (10 to 1000 Pa), depending on mass flow and pumping rates. Samples are exposed to the plasma in an open jet formed between the nozzle exit and the entrance to the diffuser. The chamber houses two model support mechanisms: a five-armed carriage and a swing-arm sting. Either stagnation-flow (see fig. 8) or wedge-shaped models can be inserted into the test stream. Water manifolds are

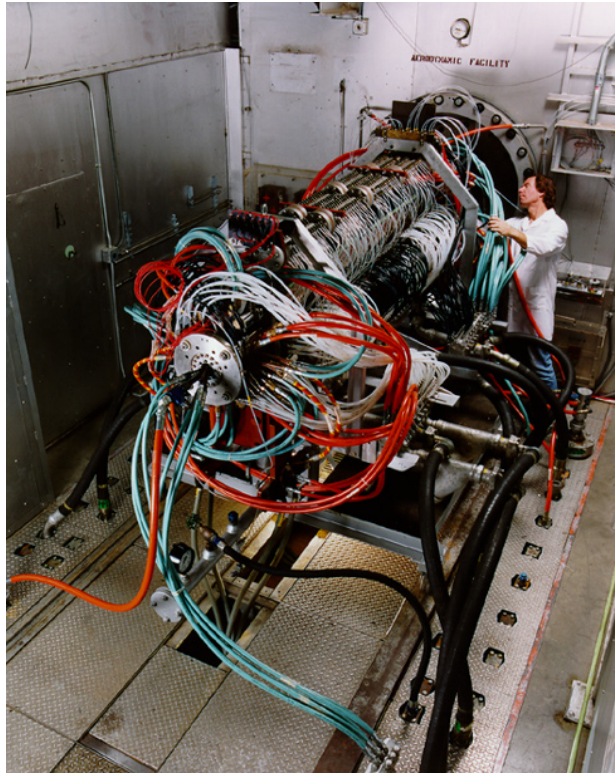


Figure 14. The segmented arc heater in the AHF

available to cool test articles. Instrumentation connections are made to a data recorder via patch panels inside the chamber. Optical access through ports on both sides and in the ceiling of the test chamber allow imaging of the test article and plasma stream.

Surface conditions on the model can be varied in two ways: nozzle area ratio and arc operating parameters (arc current and mass flow). Table 2 summarizes the physical characteristics and performance of the AHF. Figure 15 shows the range of conditions attainable on a 4 in. (10 cm) diameter sphere/cylinder stagnation test article using the segmented arc heater. Figure 16 shows the operating envelope using the Huels arc heater. Run durations as long as 30 minutes are possible, with a 45-minute cool down between runs.

AHF Mixing-Air Plenum- The capability for mixing cold gas into the arc jet stream just ahead of the nozzle throat has been added to the Aerodynamic Heating Facility. This modification greatly increases the simulation capability of the AHF particularly into a range of higher stagnation pressure and lower stream enthalpy (below 2 MJ/kg [1000 Btu/lb_m]), see figure 15.

4.1.3.2 Interaction Heating Facility

The 60-MW IHF (fig. 17) was designed to study aerodynamic heating in the thermal environment arising from

the interaction of an energetic flow field with an irregular surface. It was specifically sized for testing of large-scale models at conditions simulating the peak heating of Shuttle entry.

The IHF is equipped with a 60-MW segmented arc heater that operates with air at pressures from 1 to 10 atm (100 to 1,000 kPa) and enthalpy levels from 3,000 to 11,000 Btu/lb_m (7 to 26 MJ/kg) (air). Cold air can be added in the downstream plenum to obtain centerline enthalpies below 1,000 Btu/lb_m (2 MJ/kg). Two nozzle geometries are used in the IHF: conical axisymmetric (figure 12) and semielliptical (figure 11). The nozzles direct the flow into a walk-in, 8×8×8 ft (2×2×2 m) test chamber. Flow in the cabin is collected by the 54 in (130 cm)-diameter diffuser before being pumped into the steam-ejector vacuum system. Static pressure ranges from 0.1 to 10 torr (10 to 1,000 Pa) in the cabin, depending on mass flow and pumping rates. Samples are exposed to the plasma in an open jet formed between the nozzle exit and the entrance to the diffuser.

The test chamber houses two hydraulically-actuated model insertion mechanisms mounted on the floor of the test cabin. Tests are conducted using conical nozzles with either stagnation-flow or wedge-shaped test bodies inserted into the free-jet stream. Panels mounted at the exit of the semielliptical nozzle are exposed to a semi-open test stream. Water manifolds are available for cooling the test articles. Instrumentation connections are made to a data recorder via patch panels within the test cabin. Optical access through ports on both sides and in the ceiling of the test chamber allow imaging of the test article and plasma stream.

Two nozzle types are available for the IHF:

- Conical nozzles (10° half angle)
 - Exit diameters of 6, 8, 13, 21, 30, and 41 in (15, 20, 33, 53, 76, 104 cm).
 - Throat diameter of 2.375 in (6.033cm).
 - Used for simulation of atmospheric entry over large stagnation flow models or wedge-shaped models immersed in the test stream.
 - Variations of surface conditions are accomplished by changing:
 - nozzle area ratio, and
 - arc current and mass flow.
- Semielliptical nozzle
 - Provides a test stream suitable for flat panels up to 24×24 in (61×61cm) in boundary layer heating environments (see fig. 7).

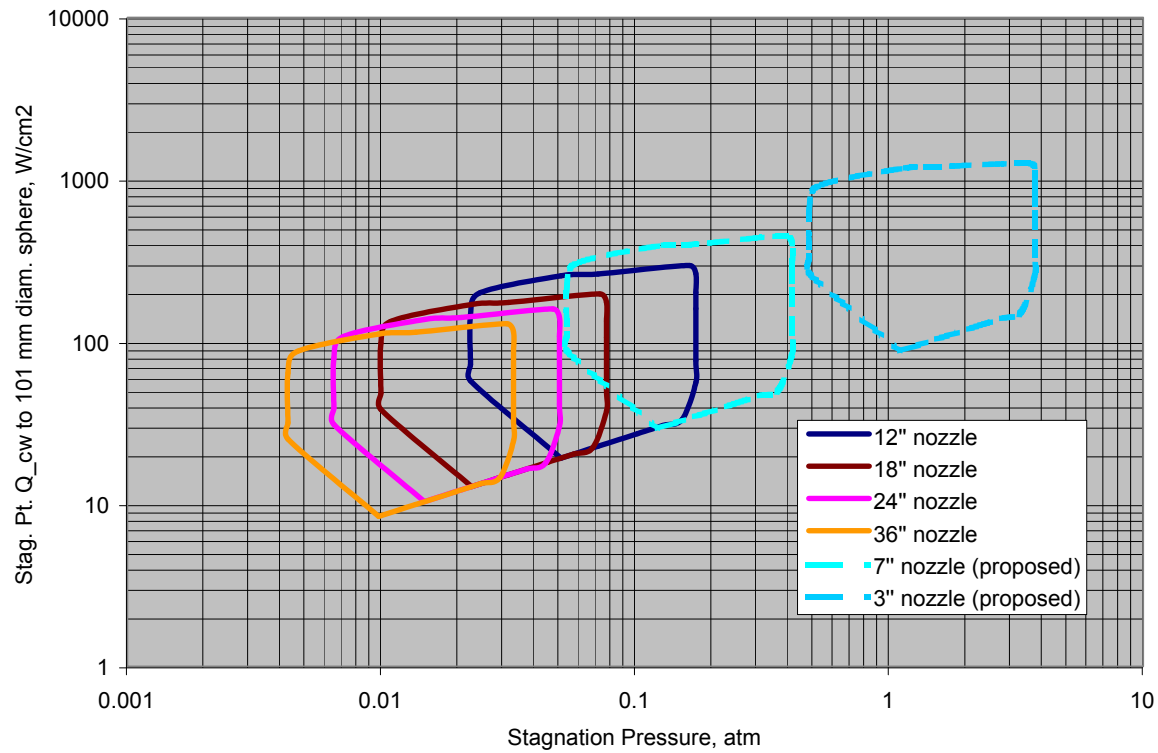


Figure 15. Operating envelope of the AHF with 20-MW segmented arc heater

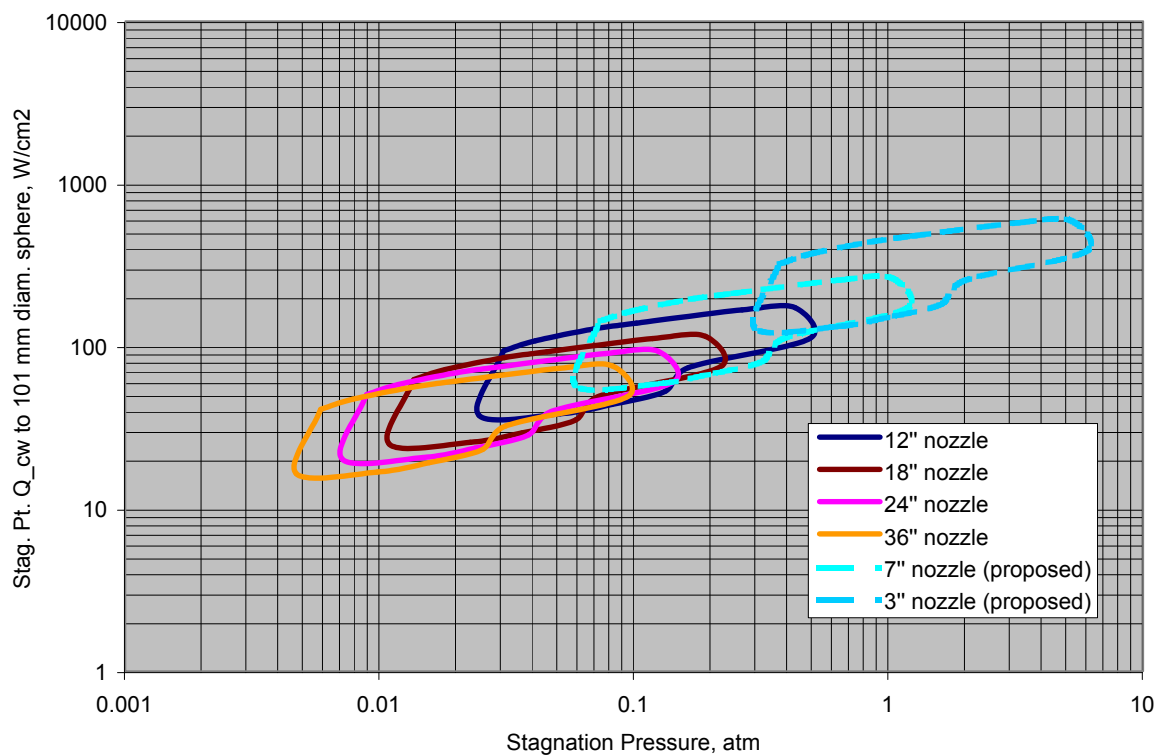


Figure 16. Operating envelope of the AHF with 20-MW Huels arc heater



Figure 17. 60-MW IHF

- Test article pivoting at the lip of the nozzle exit can be remotely inclined at angles from -8° to 8° .
- Variations of surface conditions are accomplished by changing:
 - inclination angle of the tilt-table, and
 - arc current and mass flow.

Physical and performance figures for the IHF are given in table 2. The envelope of stagnation-point conditions attainable on a 4-inch-diameter sphere/cylinder in the IHF is shown in figure 18. The operating envelope for the semielliptical nozzle is given in figure 19. Run durations as long as 30 minutes are possible, with a 30-minute cool down between runs.

4.1.3.3 Panel Test Facility

The 20-MW Panel Test Facility (fig. 20) consists of a 20-MW segmented arc heater coupled to a semielliptical nozzle. The nozzle discharges in a semifree jet within a $4 \times 4 \times 4$ ft ($1 \times 1 \times 1$ m) test cabin where the panel test fixture attaches at the nozzle exit (fig. 21). The test stream is suitable for the simulation of boundary layer heating environments on flat-panel samples of approximately 14×14 in (36×36 cm). The panels can be inclined at angles of -4° up to 15° , although 6° is the practical maximum. Surface conditions on flat-plate test articles can be varied in two ways: inclination angle of the tilt table and selection of the arc operating parameters (current and mass flow rate).

Optical access through both doors and the roof of the test cabin allow imaging of the flow and the test article. Flow is evacuated from the test chamber by the steam-ejector vacuum system, providing static pressures in the range of 0.1 to 10 torr (10 to 1,000 Pa). Water cooling manifolds are available inside the test chamber for cooling of test article components.

The heater operates at pressures from 1 to 10 atm (100 to 1,000 kPa) and enthalpy levels from 1,000 to 14,000 Btu/lb_m (2 to 33 MJ/kg) (air). The lower enthalpy range is achieved by mixing cold air with the test stream in the plenum, or downstream electrode package. The PTF simulates some of the conditions experienced by the Space Shuttle heat shield tiles, such as heat flux, surface pressure, and gap flow, and has been used extensively in Space Shuttle heat shield development and certification. Other test programs in the PTF have focused on testing flexible thermal protection blankets for next-generation reusable launch vehicles. The envelope of surface conditions on the test article for the PTF is shown in figure 22 and the physical parameters are listed in table 2 (See Appendix A). Run durations as long as 30 minutes are possible, with a 45-minute cool down between runs.

4.1.3.4 2×9 Supersonic Turbulent Flow Duct

The 2×9 Supersonic TFD is unique because panels of TPS materials can be exposed to turbulent boundary layer flow at a relatively high enthalpy. The test section has a rectangular cross section measuring 5×23 cm (2×9

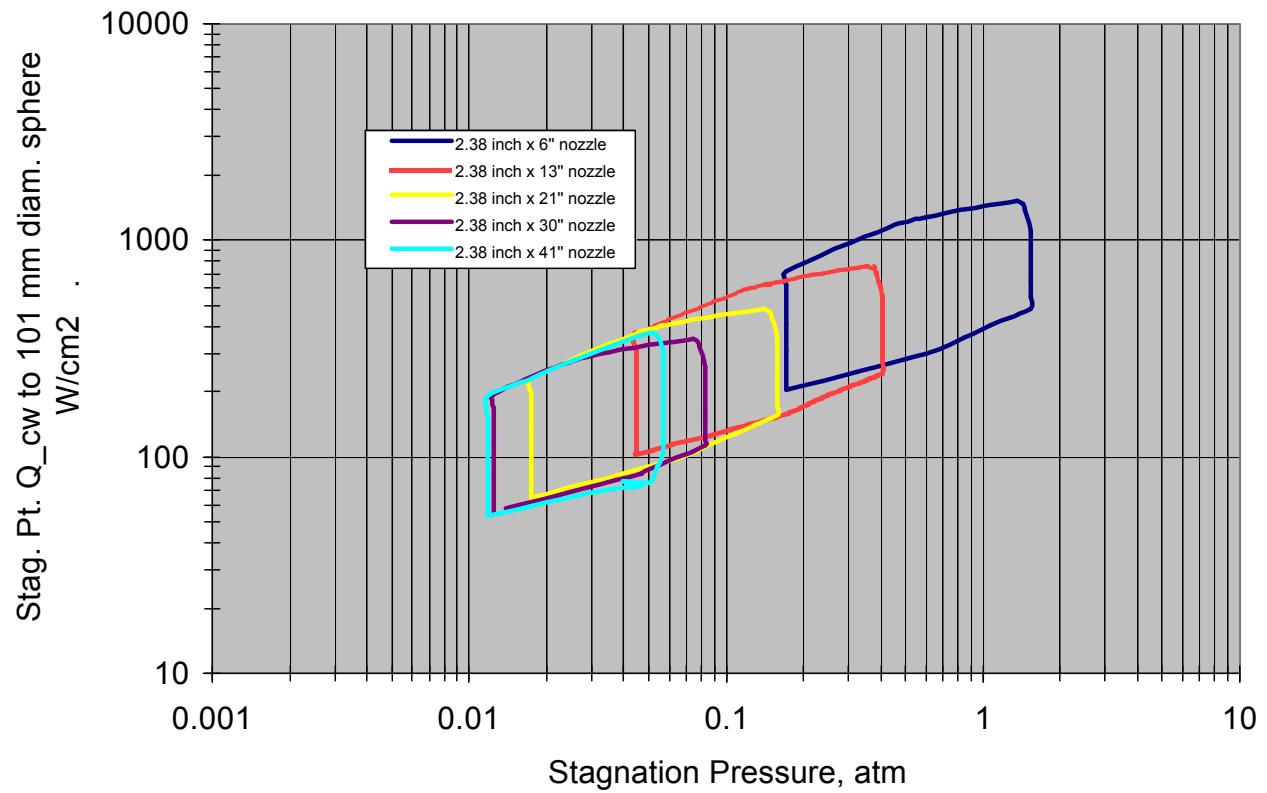


Figure 18. Operating envelope of the IHF with conical nozzles

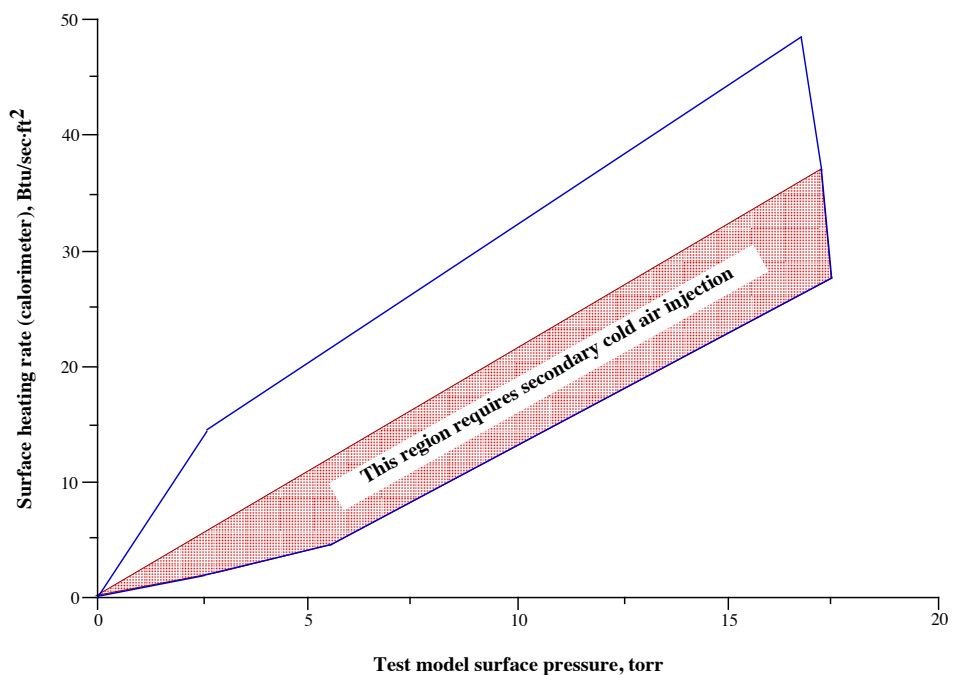


Figure 19. Operating envelope of the IHF with semielliptical nozzle



Figure 20. 20-MW PTF

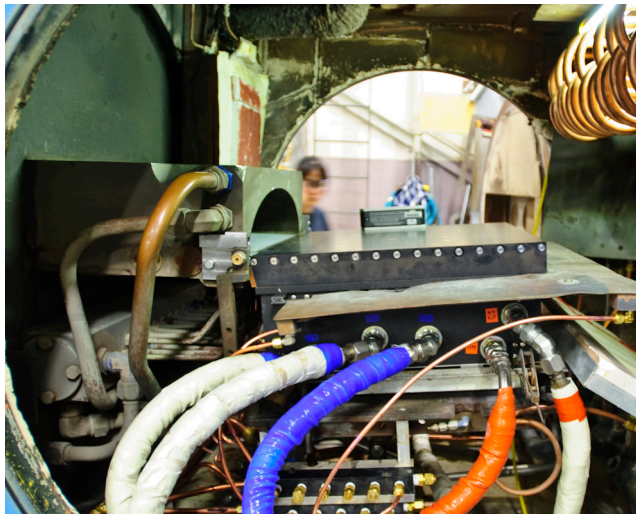


Figure 21. Calorimeter Plate installed in the PTF test cabin

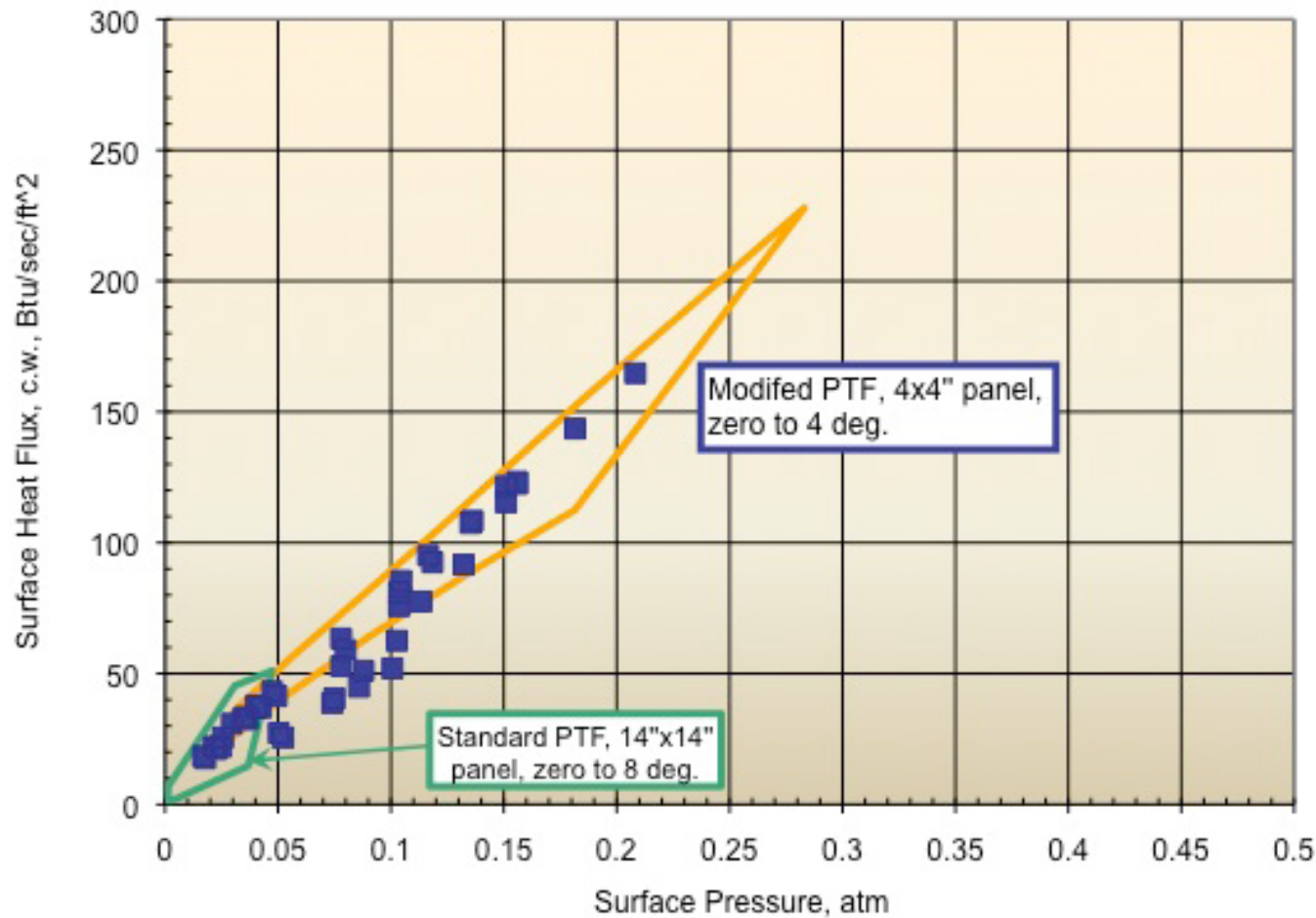


Figure 22. Operating envelope of the PTF

inches, hence its name). The test article, of dimensions 20×25 cm (8×10 inches) or 20×50 cm (8×20 inches), is mounted flush to the 23 cm (9 inch) side of the test section. The opposite wall of the test section is instrumented with pressure ports and flush-mounted calorimeters (heat-flux gages). The nozzle is also instrumented with pressure and heat-flux ports at various locations.

Features of the TFD include:

- A 20-MW Huels arc heater provides flow enthalpy in the range 3.5 to 9.3 MJ/kg (1,500 to 4,000 Btu/lb_m) (air).
- Maximum arc heater power input is about 12 MW because of cooling limitations of the nozzle throat.
- The reservoir pressure ranges from 1 to 20 atm (100 to 2,000 kPa).
- Heat fluxes up to 60 Btu/sec-ft² (70 W/cm²) (cold wall, air) can be applied to flush, wall-mounted test articles; higher heat fluxes are applied to inclined wedges.
- Surface temperatures of 3,000°F (2,000°C) have been routinely produced on TPS tile samples.
- Simulation conditions on the test article are con-

trolled by varying the arc current and air mass flow rate through the arc heater.

The physical and performance parameters of the TFD are listed in table 2. Figure 23 shows the operating envelope based on surface temperature and pressure of the test article for this facility. Other test gases available are nitrogen and argon. Run durations as long as 30 minutes are possible, with a 45-minute cool down between runs. The TFD has performed thousands of tests since its construction in 1970 and has the capability for quick turnaround and high production rates. An extensive series of development and certification tests were performed in this facility during the Space Shuttle thermal protection development process.

4.1.4 Facility Interfaces

The interfaces between investigator-supplied test equipment and the arc jet facilities are described briefly in this section. Although attempts have been made to standardize these interfaces as much as possible, some flexibility is required. Thus it is recommended that investigators coordinate these interfaces closely with the test engineers to ensure that nonstandard interfaces can be accommodated. Adhering to the interfaces listed herein will ensure the

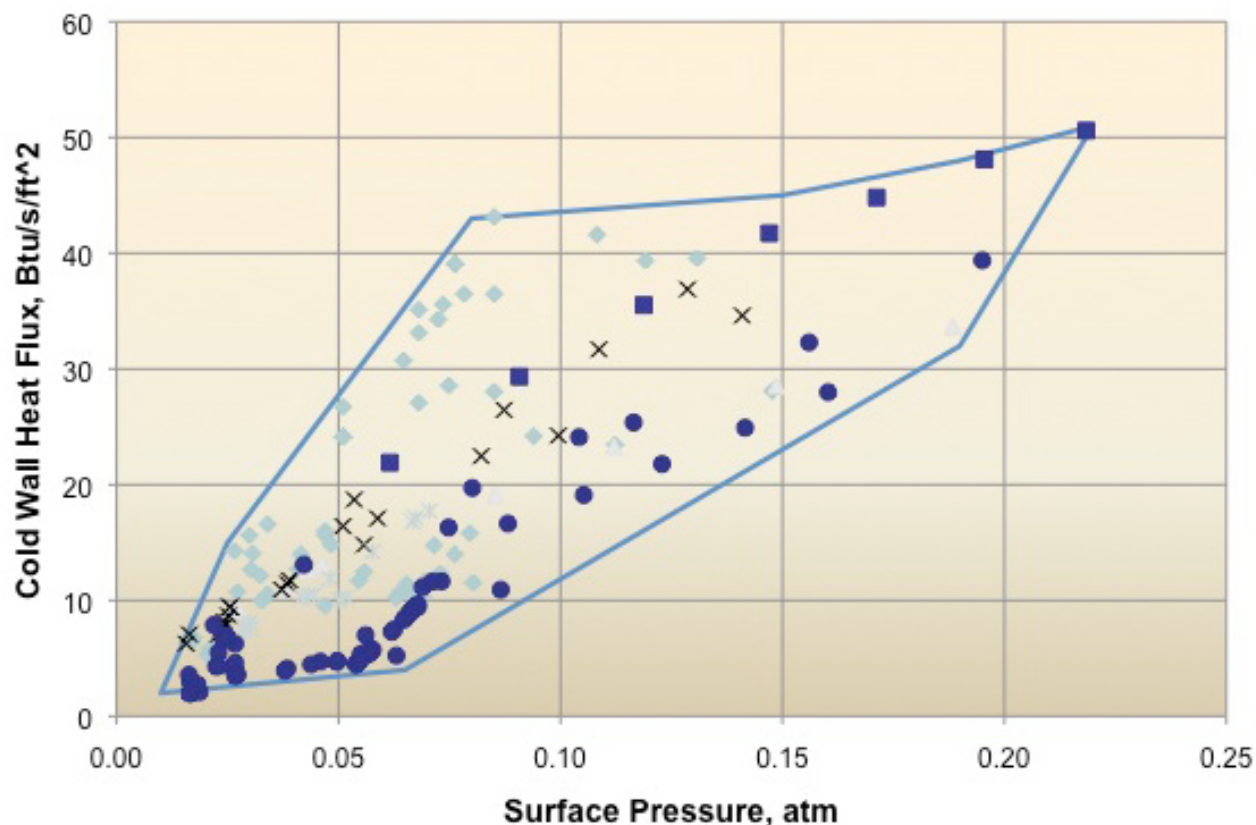


Figure 23. Operating envelope of the TFD

Table 3. Minimum lead-length requirements and number of channels supported

Facility:	IHF		AHF	PTF	TFD
Nozzle*:	Conic	SE	Conic	SE	2D
Minimum Lead Length [feet]	1	1	1 - 4 [†]	42 1	42 1
Total Harness Length [feet]	30	12	20	10	8
Channels for customer use: ‡					
Model	24 Iso	48 Iso	53 Std	20 Iso / 26 Std	
Test Dependent	12 Std	16 Std			

* Nozzle Types: Conic, SE = Semi-elliptic, 2D = 2-Dimensional Rectangular Duct

† 1' if instrumentation is 4 or less T/Cs; 4' if 5 or more T/Cs or other types of instruments

‡ Model Channels are hard wired from the Test Chamber junction panel to a Data Acquisition System analog input. "Iso" indicates a signal isolator (2kV) is connected inline with these channels. "Std" indicates "standard" channels that do not have a signal isolator. Test Dependent inputs can be made available for use from the Test chamber terminal or at the Data System enclosure, with sufficient notice and setup time.

smoothest installation of test models and minimum delay to the test schedule.

4.1.4.1 Test Article Instrumentation

Instrumentation signal outputs are acquired and recorded by a common system of hardware and software in the ARC Arc Jet Complex. This system is described in section 4.1.5.8. Typically, customers supply test articles with the following types of sensors installed in them for recording by the arc jet data acquisition system: thermocouples, pressure ports, and heat-flux gages (Gardon type). Other types of sensors can also be accommodated. Because the arc jet facilities differ physically from each other, each facility has its own unique hookup configuration for instrumentation. Table 3 defines the minimum requirements for the length of instrumentation leads and the maximum number of channels supported at each facility. For investigators who require lead lengths different from those in table 3, it is recommended that they fabricate an extension bundle, properly labeled, in order to minimize delays. Instrument leads and/or extensions shall have glass-type or Kapton insulation. For tests using the semielliptical nozzles, all instrumentation shall be electrically isolated from the test fixture (figure 26).

Installation of instrumentation into the test articles shall follow the appropriate industry standards. If the appropriate standards are not followed, the Branch can not vouch for the integrity of the resultant data. In order to certify that data from Gardon-type calorimeters is valid, these sensors must be manufactured with a thermocouple near the sensing surface: this is required for sensors being used in the IHF; and recommended for those to be used in the other arc jet facilities.

During installation into the facility, instrumentation shall be labeled sequentially (e.g., thermocouple (TC) 1 through TC 24, calorimeter 1 through calorimeter 6,

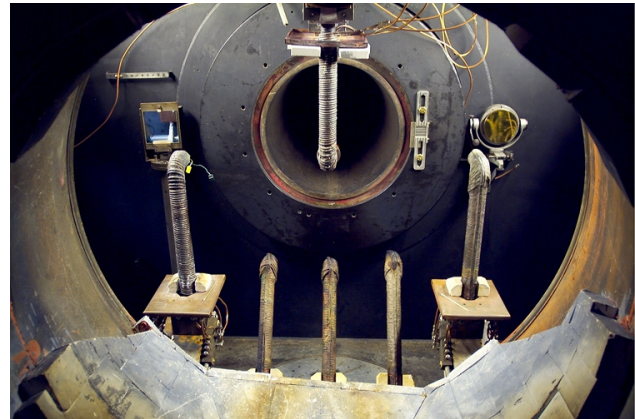


Figure 24. Typical test setup in the AHF, looking upstream

etc.). In order to avoid confusion, it is recommended that the investigator label his/her instrumentation likewise. If a nonsequential naming convention must be used, the investigator should provide dual labels: The nonsequential labels and a corresponding label that fits within the facility-specified names. It is the investigator's responsibility to keep track of the correspondence between the sequential and nonsequential naming.

4.1.4.2 Mechanical Interfaces

Mechanical interfaces can be adapted onsite, but last-minute changes can cause significant delays. The following standard interfaces are described for each facility. It is recommended that test models be fabricated to fit within the following specifications. It is requested that all test articles using high-pressure components, whether for water cooling, hydraulics, or gas systems, be hydrostatically pressure tested at the vendor's site before they are shipped to Ames. If this is not possible, prior arrangements must be made to have Branch personnel perform these checks.

AHF Mechanical Interfaces— The Aerodynamic Heating Facility is equipped with a five-arm carriage and an overhead swing arm. The minimum centerline-to-centerline distance between two stings is 11 in (28 cm); however the model support system can be operated with only the first and fifth stings in use: in this case the centerline-to-centerline distance between two stings is 44 in (112 cm). The maximum distance from the nozzle exit plane to the test article face is approximately 14 in (36 cm). Transverse motion is controlled by the facility operator during testing via a computer-controlled interface. The locations of the carriage and lifting stings are recorded by the data acquisition system.

The usual configuration in this facility has a 4 in (10 cm) hemispherical probe mounted on the overhead swing arm (containing a heat-flux gauge and a pressure tap at the stagnation point), and up to five test articles (fig. 24).

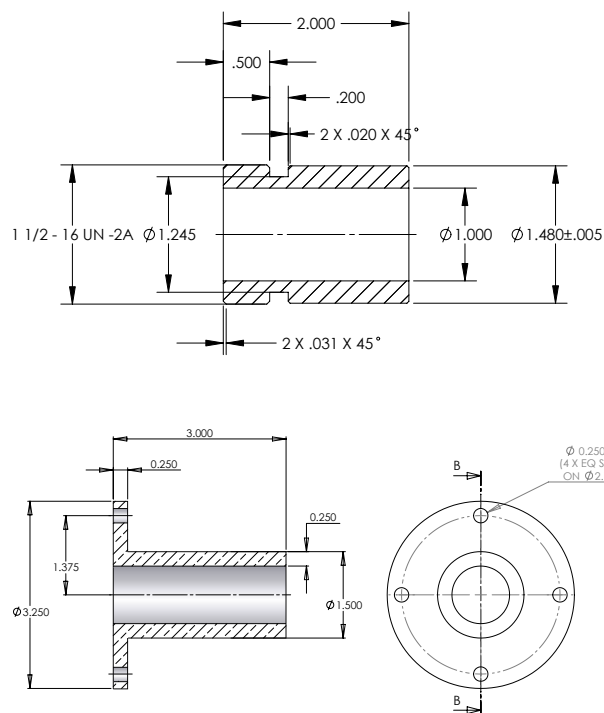


Figure 25a. Typical sting adapters for AHF

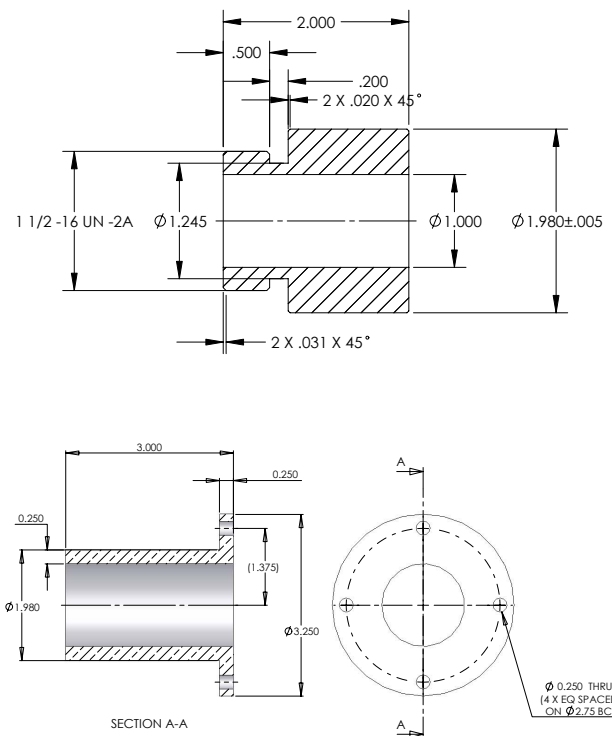


Figure 25b. Typical sting adapters for IHF

The carriage is normally operated in one of two modes: Traverse mode insert one of two models horizontally with the outermost stings locked on vertical centerline; Pop-up mode traverses up to five models to horizontal centerline while stowed below the flow stream, then lifts them up onto vertical centerline. Depending on their size and on the diameter of the nozzle exit, all models can usually be mounted to the stings in such a way that none are subsequently exposed to the flow during arc heater startup and power ramp-up to the desired test condition (duration of approximately one to two minutes). These “usual” configurations may be altered to meet individual test requirements. A major consideration in the configuration of the model support is test throughput and insertion time: Traverse mode requires approximately two seconds or less to move from the edge of the flow to the centerline and only accommodates two models; whereas in Pop-up mode, an arm can be inserted in less than one second and accommodates up to five models.

Test articles should be fabricated with an adapter that will mate with the following ID specification in order to minimize test delays: 1.5" $-.000/+0.002$ (38 mm $-0.00/+0.05$). Typical sting adapters are shown in fig. 25.

The AHF is equipped with a flexible system of water cooling for test articles. Typical cooling water pressure is 600 psig (4,000 kPa) at flow rates of approximately 150 gpm (9.5 L/s). All high-pressure components supplied by customers must be hydrostatically pressure tested and certified before installation in the arc jet facility.

PTF Mechanical Interfaces– For the PTF, which is always configured with a semielliptical nozzle, the model support system is standardized. All test articles shall fit within the test fixture provided by ARC, or one fabricated with equivalent dimensions. A schematic drawing of the test fixture is shown in figure 26, and the dimensions are shown in table 4. The test assembly is installed by passing it through a round hatch in either side wall of the 4 ft (1.2 m) test chamber (fig. 21). The hatches are of 36 in (91cm) diameter. The test fixture attaches to two pivot points, one on each side of the nozzle, such that the axis of rotation is at the lip of the nozzle. A hydraulically-actuated piston located underneath the test chamber provides calibrated tilt-table inclination angles, which are controlled manually from the control room and recorded by the data acquisition system. All instrumentation wires feed through a flexible conduit attached to one side of the test fixture. It is imperative that the instrumentation leads shall extend at

least one foot outside the test fixture, even when extensions will be used. (See fig. 26.) Water cooling manifolds are available in the PTF test chamber at a supply pressure of approximately 600 psig (4,000 kPa) and flow rates of approximately 100 gpm (6 L/s). All high-pressure components supplied by customers shall be hydrostatically pressure tested and certified before installation in the arc jet facility.

IHF Semielliptical Nozzle Mechanical Interfaces– For the IHF with the semielliptical nozzle, the model support system is standardized. All test articles must fit within the test article fixture provided by ARC, or one fabricated with equivalent dimensions. A schematic drawing of the test fixture is shown in figure 26, and dimensions are shown in table 4. The test fixture attaches to two pivot points, one on each side of the nozzle, such that the axis of rotation is at the lip of the nozzle. The test assembly is installed by passing it through round hatches in the west wall and the ceiling of the walk-in test chamber, or through the 5×2 ft (150×61cm) main access door (fig. 27). The hatches are of 35 in (89cm) diameter. A hydraulically-actuated piston located underneath the test chamber

provides calibrated tilt-table inclination angles, which are controlled manually from the control room and recorded by the data acquisition system. All instrumentation wires feed through on one side of the test fixture. It is imperative that the instrumentation leads shall extend at least one foot outside the test fixture, even when extensions will be used. (See fig. 26.) Water cooling manifolds are available in the IHF test chamber at a supply pressure of approximately 600 psig (4,000 kPa) and flow rates of approximately 250 gpm (16 L/s). All high-pressure components supplied by customers shall be hydrostatically pressure tested before installation in the arc jet facility.

IHF Conical Nozzle Mechanical Interfaces– When a conical nozzle is installed in the IHF, the IHF is equipped with two swing-arm model supports: one each on the west and east side, mounted on the floor of the test chamber (see figure 28). The inside-diameter bore of the model stings is normally 2.0" $-.000/+0.002$ (51mm $-0.00/+0.05$). Test articles shall be fabricated with a shaft/adapter to interface with these bores; the shaft/adapter shall be at least 1 1/2 diameters in length. Typical sting adapters are shown in fig. 25.

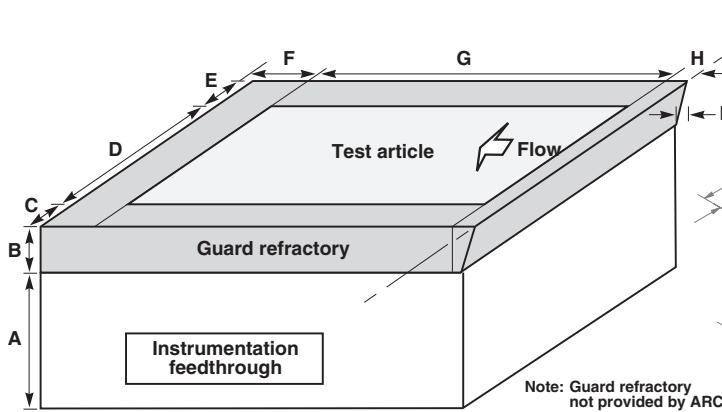


Figure 26a. Test fixture assembly for PTF and IHF (semielliptical nozzle) (dimensions are in table 4)

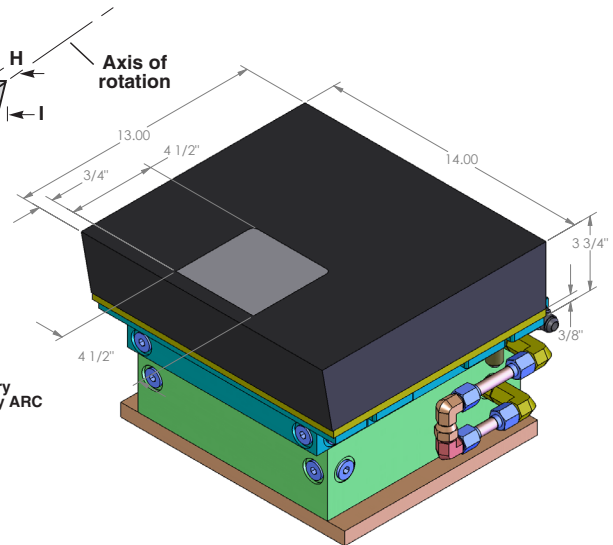


Figure 26b. Typical model assembly for TPTF

Table 4. Dimensions for IHF and PTF panel test fixtures (drawing shown in fig. 26a)

Callout, fig. 26a	A*	B*	C*	D*	E*	F*	G*	H*	I*
PTF	5 7/8	2	2 1/8	15 3/4	2 1/8	2 1/8	15 3/4	1 1/8	3/8
IHF	5 7/8	2	3	30	3	4	30	2	3/8

*All dimensions are in inches.

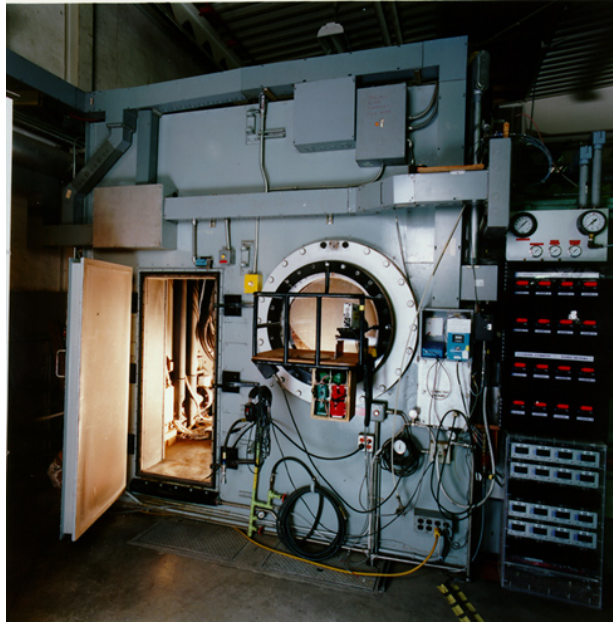


Figure 27. Main access door for the IHF

TFD Mechanical Interfaces— A schematic representation of the mounting of the test article for the TFD is shown in figure 13. In this facility, the test articles are flush mounted on the wall of the test section. Test panels measuring 8×10 in (20×25 cm) or 8×20 in (20×50 cm) can be mounted in the TFD. The test panels are secured in place by bolts around the perimeter of the backing flange of the test article. Instrumentation feedthrough connectors supplied by ARC are used to patch sensor data out of the back of the test-article flange and into the data recording system. Water cooling manifolds are available.

4.1.4.3 Optical Access

All the arc jet facilities have optical access to the test articles. The flow stream and test article(s) in the AHF, PTF, and IHF are accessed through large windows in the test chambers for instrumentation and line-of-sight observations. (See table 5.) The TFD has limited access for optical instrumentation through existing heat-flux sensor ports in the wall facing the test article.

In addition to the standard facility monitoring instrumentation, ARC will provide optical pyrometers and will coordinate photographic and video coverage of the tests, as required by the investigator. (A list of the optical pyrometers supplied by ARC is given in table 6.)

4.1.4.4 Personnel Access Outside the Test Chamber

Access to the area immediately outside the test chamber during a run is limited because of the safety aspects of high-voltage and high-pressure systems. If needed, such

access must be coordinated with the test personnel during the planning phase of the test program.

4.1.4.5 Model Sizing/Configuration Guidelines

A general rule of thumb that may be used in determining the maximum dimensions of proposed test articles is that the areal blockage ratio should not exceed 0.25 to 0.30. The size of test articles that can be successfully tested in the facilities depends on the geometry of the test articles; thus this rule of thumb is offered only as a general guideline.

It has been a general practice at Ames to produce blunt-body stagnation test articles for arc jet tests with a radius of curvature on the front, forward-facing surface. This is especially important for small bodies where the velocity gradient in the stagnation region is greater than it is for larger ones. Unavoidably, there are slight misalignments of the test bodies relative to the flow vector when inserted into the flow stream, and these unwanted variations in angle of attack will occur between test runs. For a test article with a radiused front surface, the flow field over the front surface will be less sensitive to change under conditions of unanticipated angle of attack. Given an unwanted yaw, the stagnation point will 'move' away from the desired location at the center of the blunt cylinder, causing non-uniform velocity gradients and heat flux to the test article. This effect accounts for some of the scatter in calibration data from run to run at the same facility operating conditions and is one of the reasons why hemispheres are chosen as the standard shape for calorimeters.

4.1.5 Instrumentation Options

4.1.5.1 Calorimeters

ARC can provide a selection of heat-flux (and/or pressure) sensing devices for characterizing the flow environ-



Figure 28. Typical test setup in the IHF

ment for both stagnation and flat-plate tests. Some of these instruments are water cooled for continuous operation, others are transient, uncooled sensors.

A family of hemisphere/cylinder probes designed for the AHF are available, ranging in diameter from 2.5 to 4 in (6.4 to 10 cm). Each contains a removable Gardon-type heat-flux sensor at the stagnation point, and a pitot pressure port located just off the stagnation point. Blunted-cylinder probes of the same design are also available. Additionally, a set of water-cooled 5/8 in (1.588cm)-diameter hemisphere/cylinder probes are available for both the AHF and the IHF (for use with the large nozzles). Each probe contains one of either a heat-flux sensor or a pitot pressure port, located at the stagnation point.

Slug-type calorimeter probes are also available. These are recommended for the high-heat flux environment of the IHF 13 and 6 in (33 and 15 cm) conical nozzles. These probes are available in: 2.4, 3.0, and 4 in (6.1, 7.6, and 10 cm) -diameter hemispherical probes; 4.0, 5.0, 6.0, and 8.0 in (10, 13, 15, and 20 cm) -diameter flat-faced cylinders with a 0.375 in (0.953 cm) corner radius; and 3.0 and 4.0 (7.6 and 10 cm) iso-q (base radius = nose radius) geometry. Most of these probes are also equipped with a pitot pressure port. Other configurations are available by special request. Figure 29 shows a selection of slug calorimeters: 3-in hemisphere, 4-in iso-q, and 6-in flat face.

Several null point calorimeters are also available to map the heat flux distribution of the test stream. These consist of a 15°-taper cone with a 0.18-in (4.6 mm) nose radius.

Water-cooled calibration plates that mount in the loca-

Table 5. Available IR-quality viewports

	AHF		PTF		IHF	
	Number	Diameter (in)	Number	Diameter (in)	Number	Diameter (in)
Side-view	1	11	4	6	3	10
	2	6				
	2	4				
Top-view	0	—	5	6	6	6

tion of the test article are available for both the PTF and the IHF with the semielliptical nozzle. (See fig. 26.) The plates are equipped with Gardon-type calorimeters and static pressure taps distributed throughout the surface of the plate in order to obtain distributions along the test surface.

The wall opposite the test panel in the TFD is instrumented with heat-flux sensors and static pressure ports.

4.1.5.2 Pyrometers

The Thermophysics Facilities Branch will provide optical pyrometers to support measurements of surface temperature. Several models are available and are listed in table 6.

4.1.5.3 IR camera

TSF will provide IR recording of the test samples. At this time, however, these are qualitative images that show relative temperature distributions. Absolute-temperature calibration of the IR cameras can not be provided.



Figure 29. Examples of typical slug-calorimeter probes

Table 6. Optical pyrometers provided by ARC

Manufacturer	Model	Serial Number	Type	Temperature Range	Spectral Response (μm)	Field-of-View (FOV) Ratio
Mikron	M90V	44384	Infrared	900–3000C	0.65mm	300:1
Mikron	M190V	M0036265	Infrared	800–3000C	0.65mm	300:1
Mikron	M190V	M0026257	Infrared	900–3000C	0.65mm	300:1
Mikron	M190V	M0031934	Infrared	900–3000C	0.65mm	
Mikron	M90H	44388–1	Infrared	600–3000C	0.78–1.06	180:1
Mikron	M90H	44388–2	Infrared	600–3000C	0.78–1.06	180:1
Mikron	M190H	50195	Infrared	600–3000C	0.78–1.06	180:1
Mikron	M190H	000866–1	Infrared	600–3000C	0.78–1.06	180:1
Mikron	M190H	000866–2	Infrared	600–3000C	0.78–1.06	180:1
Mikron	M190H	M0026255	Infrared	600–3000C	0.78–1.06	180:1
Mikron	M190H	M0026256	Infrared	600–3000C	0.78–1.06	180:1
Mikron	M190HX	21289	Infrared	1200–3500C	0.78–1.06	180:1
Mikron	M190HTS	921	Infrared	600–3000C	0.78–1.06	180:1
Mikron	M190V–TS	M0030936	Infrared	1000–3000C	0.65	300:1
Mikron	M90Z–B	50875	Infrared	–50–1000C	8.0 – 14	180:1
Mikron	M90Z–B	27158	Infrared	–50–1000C	8.0 – 14	180:1
Mikron	M90R2	50194	Infrared	900–3000C	2-Color*	180:1
Mikron	M190R2	5615	Infrared	900–3000C	2-Color*	180:1
Mikron	M190R2	21526	Infrared	900–3000C	2-Color*	180:1
Mikron	M190R2	M0026258	Infrared	900–3000C	2-Color*	180:1
Mikron	M668L	50550	Inf./fiber Op	900–2500C	0.78–1.06	60:1
Mikron	M668L	50482	Inf./fiber Op	700–2600C	0.78–1.06	180:1
Mikron	M668L	21304	Inf./fiber Op	800–3000C	0.78–1.06	300:1
Mikron	M668L	M0019077	Inf./fiber Op	1200–3500C	0.78–1.06	300:1
Mikron	M668L	M0032015	Inf./fiber Op	1500–5400F	0.78–1.06	300:1
Mikron	M668L	M0032016	Inf./fiber Op	1500–5400F	0.78–1.06	300:1
Mikron	M668L	M0026259	Inf./fiber Op	1500–5400F	0.78–1.06	300:1
Mikron	M680	19838	Inf./fiber Op	900–3600C		300:1

*2-color response bands are 0.78–1.06 μm and 0.9–1.06 μm

4.1.5.4 Video and Photographic Documentation

Video and photographic recordings of the tests are always provided. The standard arc jet photographs typically comprise three views of the test samples: front, side, and oblique. These are taken both pre- and post-test. Additional views will be taken as required to document any abnormalities that may have occurred during testing, or any features of particular interest.

Video views depend upon the facility in use. Three views are standard in IHF: front-view, typically recorded off of a mirror, side view, and top view. Two views are standard in AHF and PTF. In AHF, typically a front view (also off of a mirror) and a side view are provided. In PTF, a top view and side view are standard. For TFD, video recording is a challenge and currently, a standard view has not been established.

Additional views and photographs can also be accommodated. These must be requested in the test plan.

4.1.5.5 Laser Induced Fluorescence Measurements

Laser-induced fluorescence (LIF) is a non-intrusive optical technique for single-point measurements of free stream flow properties. The technique targets atomic oxygen and atomic nitrogen to determine species density, static temperature, and flow velocity at a point on the flow centerline downstream of the nozzle exit. Coupled with known facility flow rates and a pitot pressure measurement, the LIF measurements are used to determine the stream enthalpy and the degree of chemical nonequilibrium at the measurement location. Models are not in the stream when LIF is used. LIF measurements are typically performed during the calibration phase of a test series. LIF measurements have been implemented in IHF only.

4.1.5.6 Photogrammetric Recession Measurement

Photogrammetric Recession Measurement (PRM) is an optical technique for measuring the recession time histories of an arbitrary number of points distributed over the face of a TPS test article during testing. It is non-intrusive, requires no external light source (in particular, no lasers), and requires no modifications to the test article. The principal requirements of PRM are: (1) that the face of the model exhibit some texture as it ablates; and (2) that the ablating surface can be imaged from at least two directions.

A typical PRM system consists of two high-resolution ($2K \times 2K$ pixels) video cameras; neutral density filters to attenuate the light that reaches the cameras; a PC computer with camera interface cards and software for acquiring images; one mirror for each camera mounted to

the bulkhead of the test cabin to reflect light from the test article to the camera; and an external signal generator to provide a pulse train that synchronizes the cameras. Also required is a calibration object that can be installed at the position of the test article before or after a test. This may be a flat plate with a rectangular array of targets mounted on a micrometer-driven translation stage. Finally, custom software is used for calibrating the cameras and extracting recession data from the camera images.

PRM has been applied in many tests in the Interaction Heating Facility. Measurements have been made on flat-faced and iso-q stagnation models and on wedge-mounted panel models. For stagnation models, the diameter of the arcjet nozzle and the distance of the model from the nozzle exit plane are the test-geometry variables that most affect the viewing angles of the face of the test articles and thus the feasibility of making PRM measurements. With a 13-in nozzle, the model should not be less than 10 in from the nozzle. PRM measurements have also been made on 3-in dia iso-q models tested in the 8-in extended nozzle where the models were 6 in from the nozzle exit plane. For tests in both the 13-in and 8-in extended nozzles, one camera was mounted on top of the test cabin and pointed at a mirror mounted to the upstream bulkhead at about 1:00 o'clock relative to the nozzle. The second camera was mounted on the west side of the test cabin and was pointed at a mirror at about 8:00 o'clock. Measurements have been made on wedge-mounted panel models in the 6-in nozzle. For these tests, the west camera viewed the face of the model directly, and the mirror for the top camera was at about 10:00 o'clock.

It can take up to several hours to install and calibrate a PRM system. The most time-consuming part is aligning the mirrors and cameras. Calibration involves installing the calibration object and imaging it in several positions. This can take about 30 min. Data acquisition simply involves recording images from the cameras and adjusting the camera exposures by adjusting the duty cycle of the signal from the signal generator. The alignment of the system should be checked before each run by acquiring arc-off images. Much longer exposures are required than for data acquisition because the model is no bright. Images are typically recorded at 16 Hz for runs of 1 min or less; lower rates are recommended for longer runs. The imaging rate corresponds to the frequency of the synchronizing pulse train and thus is controlled at the pulse generator. Data reduction is a computationally intensive process and that can take one to several hours, depending on the number of measurement points. The product of PRM measurements is the recession time history at each measurement point.

4.1.6 Facility Support Equipment

The arc jet complex is serviced by common facility support equipment that is shared among all the arc jet facilities described in this section. In many cases, the frequency of facility operations is determined by the availability of these support systems. Only one arc jet facility may be operated at any time because of safety considerations as well as the need to share common support equipment.

4.1.6.1 Steam-Ejector Vacuum System

The Steam Vacuum System (SVS) servicing the arc jet complex is one of the largest steam-ejector vacuum systems of its type. The SVS provides the high-mass-flow vacuum conditions required for arc jet facility operations. Each of the arc jets is plumbed into the SVS via large-diameter piping and isolation gate valves. The SVS consists of five stages of steam ejectors that are operated in series. Figure 30 shows a schematic diagram of the SVS; the SVS is visible in figure 5. The steam is provided by a natural-gas-fired boiler with a generating capacity of 200,000 lb/hr (25 kg/s). Using all five stages, the system pumps to a blankoff (no flow) pressure of 80 microns of mercury. Five-stage operation can pump 0.5 lb_m/sec (0.2 kg/sec) of air while maintaining a plenum pressure of about 100 microns (0.1 torr). Using three stages, the

capacity is about 3 lb_m/sec (1.4 kg/sec) at 3 torr (400 Pa). A standby operating mode is used to save energy between tests when two stages are operated, producing about 15 torr (2 kPa) with no gas flow.

4.1.6.2 60-/150-MW dc Power Supply

Originally constructed in 1975 at 60-MW maximum power, this power supply was modified a few years later to upgrade its power capacity. This power supply is a current-controlled, three-phase, full-bridge, phase-controlled silicon controlled rectifier (SCR) type that provides the dc power source for the arc jet facilities in Building N238. It consists of six SCR module pairs, which can be configured into any compatible series/parallel combination. Each module is rated at 5500 volts open circuit, 4,350 volts into a load, and 2,700 amperes (A) continuous, 6,000 A short term. The entire power supply has a power rating of 75 MW for a 30-minute-on, 30-minute-off duty cycle, and up to 150 MW for 15 seconds. The operator selects a module configuration to provide open circuit voltage that slightly exceeds the expected arc voltage. Current is controlled via a set point manually input at the control board by the facility operator. Current and voltage are recorded on the data acquisition system. The entire power supply is isolated from ground to 33 kV.

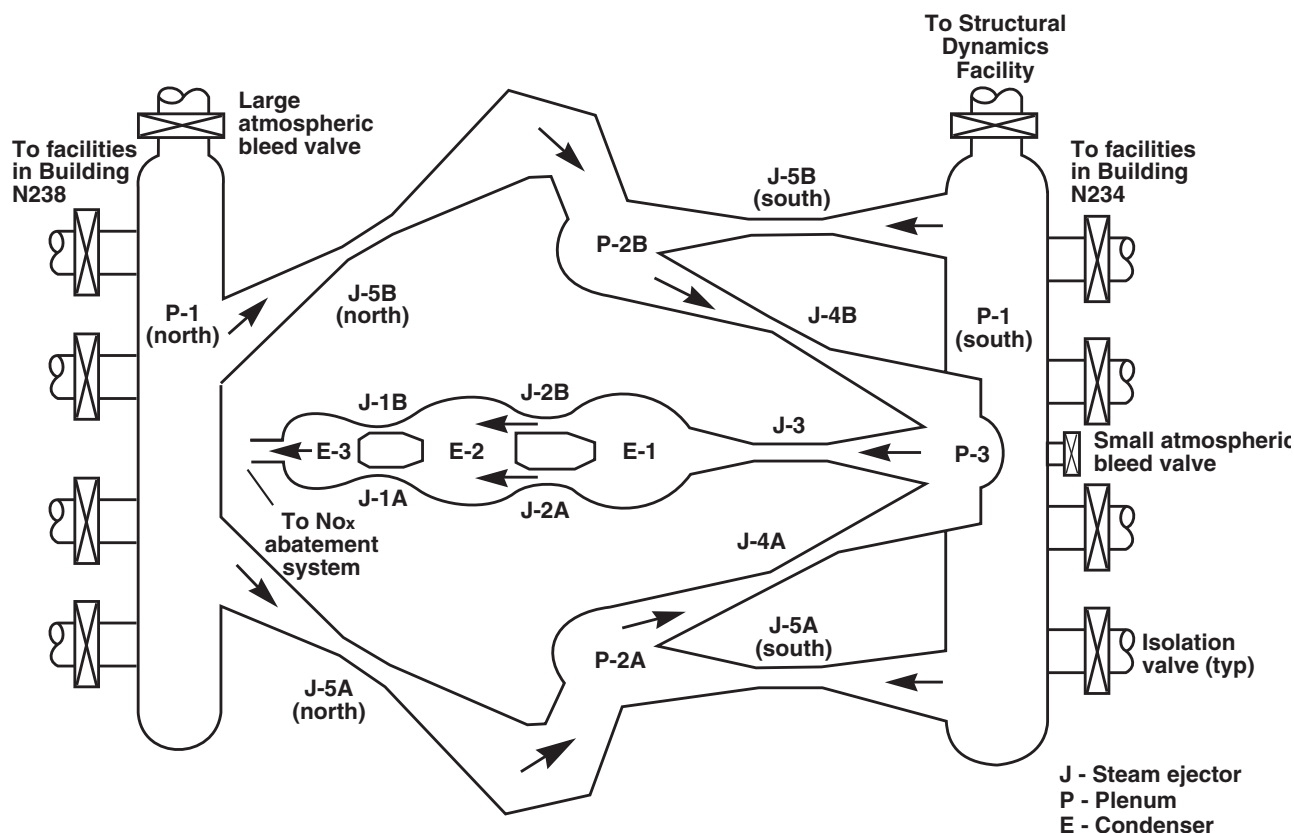


Figure 30. Schematic diagram of the five-stage SVS

The rectifier modules are fed from three double, secondary transformers that receive primary power from the distribution grid at 115 kV 60 Hz. Secondary transformers step down the voltage to 4,170 VAC feeding into the rectifier modules. Rectification is accomplished using three parallel strings of 14 SCRs, one leg for each phase. The output from each module is shunted with a double string of four free-wheeling diodes and is connected in series with a 4-millihenry inductor. The transformer secondaries are shifted 30° with respect to each other; therefore, adjacent modules connected to the output bus produce an effective 12-phase rectifier with a corresponding reduction in dc ripple.

The output from the power supply is transmitted to each of the four facility load switches in the basement of Building N238 through 3 in (8cm), water-cooled, copper piping. The power supply and its components are insulated for 33-kV dc power. The power supply is cooled by an independent, deionized, cooling water system consisting of a storage tank, a cooling tower, deionizers, a circulating pump, and associated hoses and pipes. The system uses deionized, chemically treated, low-conductivity water to cool the SCRs, free-wheeling diodes, output inductors, and the dc power bus.

4.1.6.3 20-MW dc Power Supply

The 20-MW power supply comprises five identical modules that can be connected to provide 20 MW of dc power. Each of the 5 modules consists of 2 rectifier banks (or half modules). Each half module is nominally rated for 1,600 amps at 1,250 V; open circuit voltage is 2,500 V. The 10 half modules may be connected in various combinations by using setup switches to provide a desired open circuit voltage, or desired current level, depending on the anticipated arc jet load requirement. Current is controlled manually from the bench board by means of a bias control setting, which adjusts current output via saturable reactors. There is no direct voltage control. The operating current and voltage are recorded for reference. The entire power supply is isolated from ground to 30 kV.

The power output is brought into Buildings N234 and N238 by a set of high-voltage power cables, and then is distributed to the facilities through a main load switch and individual facility disconnect switches. These switches are interlocked to prevent unwanted energizing by means of limit switches and key interlocks.

With appropriate connections between the rectifier banks, the power supply can deliver approximately 19 MW for 5 minutes and 12 to 14 MW for up to 30 minutes.

4.1.6.4 Deionized Water Cooling System

The arc jet facilities use a common, closed-loop, deionized water cooling system, which provides the majority

of the heat rejection needs. Deionized cooling water is stored in a 168,000-gallon storage tank located near the steam vacuum system. The water from this tank has been demineralized and deionized to reduce the resistivity and oxidation. The tank provides about a 40 ft (12 m) static pressure head when full.

The water system is used as primary cooling for the arc heaters, test article supports, nozzles, and other facility hardware. A set of 10 pumps circulate cooling water at approximately 8,000 gpm (500 L/s) at a pressure of 700 psig (5,000 kPa) to the selected facility and then back to the tank. A heat exchanger in a secondary circuit permits cooling of the stored water, but at a low rate.

A separate water cooling system in Building N234 (400 psig [2,700 kPa] discharge) cools the plenum heat exchanger, valve shield, etc. So-called “gravity” cooling water is also available directly from the 168,000-gallon tank at about 15-psig (100 kPa) pressure. This water is used to cool the diffuser pipes of the AHF and TFD. It is collected in a sump and then recirculated back to the main tank. City water is available at about 50 psig (350 kPa), if necessary.

4.1.6.5 Arc Jet Air System (AJAS)

The arc heaters at ARC usually operate with air as the main test gas. Dry air with dew point better than -40 °F (-40 °C) is supplied by a 3,000 psi (20 MPa) distribution system located at ARC. The primary storage facility used by the Arc Jet Complex has a storage capacity of 1 million standard cubic feet (28,300 cubic meters) and fed by two (2) reciprocating compressors, each capable of keeping up with normal operations. Air flows into air control panels located in the basement below each arc jet facility. From there the bench board controls are used to command a PLC to regulate the flow rate of air to a facility via manual or automated controls actuated by the facility operator. Air can also be used for auxiliary purposes such as moving or cooling portions of test articles.

4.1.6.6 High Pressure Gases—Nonair

The arc heaters at ARC can operate with gases other than air as the main test gas.

- **Nitrogen**—A liquid nitrogen storage tank feeds a 4,000 psig (30 MPa) pressurized nitrogen gas storage tank yard located near the 60-MW power supply. Piping distributes the nitrogen to facilities in Buildings N234 and N238. The nitrogen can be used as a main test gas (AHF only) or as an auxiliary gas for purging, cooling, or other purposes.
- **Argon**—Argon gas is used by the constricted arc heaters in small amounts at all times. A small flow of argon is used to aid in starting the arc discharge at

the beginning of each run. A small amount of argon is also injected between constrictor disks and electrode rings to reduce the occurrence of arcing between adjacent components of the arc heater. In addition, the AHF can be operated with argon as a main gas.

- **Other gases**— Other gases can be used as needed.

4.1.6.7 Air Pollution Control System

Nitrogen oxides in the exhaust streams produced by the arc heaters must be removed before exhausting into the atmosphere. Removal is accomplished by a combination containment and scrubbing system, which neutralizes the resultant nitric acid with a caustic solution. Air discharge quality is monitored continuously for compliance with local ordinances.

4.1.6.8 Data Acquisition System

The current arc jet data acquisition system consists of Intel PC-based workstations. Test data storage is accomplished by a host workstation for each of the arc jet facilities. Data reduction is accomplished on either the facility host or a central data storage workstation for post-run analysis. Any fourteen channels may be displayed and changed at any time during the test without loss of data. Seven of these can be plotted on a chart showing % Full Scale vs. Time; the other seven are displayed numerically. Sampling rates may be changed during a run via software input to the data system controller interface. Output is available in the form of: printed columnar data as a function of time; electronic files of the tabular data as a function of time; or graphical plots of multiple data channels. The system network is isolated from the Internet for reasons of security and data integrity, but under proper security protocols, data can be transmitted via the Internet to remote sites. Each facility has a standard set of facility data that is always acquired, but may not appear on reduced test data reports. With some variation, the required report data include: arc voltage, arc current, power supply bus voltage, air and argon system mass flows, arc heater pressure, and test chamber vacuum level. In some cases, other data are reported as facility data, including individual electrode current levels.

Each facility has dedicated front-end equipment designed to condition the sensor signals, digitize them, and pass them to the facility host computer. The host computer is connected via fiber-optic ethernet link to an operator console and display that controls the host during the run. The fiber-optic link provides an important isolation from high-voltage potentials induced on test articles and the arc heater itself. All data channels from the arc heater and test article are thus isolated by this system from operators. In addition, all channels from the test articles must be ungrounded, or electrically floating and, if subject to charging

by the arc jet flow, may first pass through a standard isolator. Exceptions are made for Huels arc heaters whose downstream electrodes are electrically at zero potential, or grounded.

Specifications of the ARC arc jet data acquisition system are as follows:

- Intel PC- workstation for data acquisition, remote system control, data reduction, and online storage
- VXI-based data system front end
 - Chassis controller: National Instruments VXI-MXI-2
 - Provides interface between VXI system and host computer.
 - KineticSystems Corp. V207 analog-to-digital converter
 - Capable of 500,000 samples per second, aggregate
 - 16-bit resolution (one part in 65,536)
 - KineticSystems Corp. V243 96 or 48-channel, Low-level Signal Conditioner and Multiplexor
 - Programmable gain from 1 to 2000
 - KineticSystems Corp. V246 8-channel Bridge Signal Conditioner
 - Programmable gain from 1 to 1000
 - Capable of use with Wheatstone bridge-type transducers
 - Used in the Interaction Heating Facility for test chamber channels
 - Channels are equipped with setable filters
- Acquisition Parameters:
 - Data Rate
 - Sample rates range between 10 seconds/sample to 5000 samples/second/channel

Note: Actual maximum data rate = $500 \text{ kS/s} / [\text{Total number of recorded test and facility channels}]$, rounded to the next lower interval of 1, 2, or 5. Recorded data rates can be any whole number division of the maximum rate. Example: With 96 channels, the maximum rate is 5kS/s and available rates are 5k, 2.5k, 1.66k, ..., 0.1 S/s/ch.

Lower data rates are achieved by run-time oversampling (record the average of N samples acquired at the maximum rate) or

- decimation (record every Nth sample of the maximum rate). Post-test oversample averaging is available to reduce perturbations and report size.
- Capable of selecting any sample rate at any time during the test
- Real-time display
 - Real-time computations for display of any 14 channels
 - Capable of selecting any 14 channels at any time during the test
- Data reduction processing is complete within minutes after each run, depending on the data file size.
 - Post-test oversample averaging is available to reduce perturbations and report size.
- Test article sensors:
 - Thermocouples: types B, C, D, E, G, J, K, N, R, S, and T
 - Pressure transducers
 - Calorimeters: slug, null-point, and Gardon
 - Radiometers
 - Pyrometers
 - RTDs
 - Venturi flow meters
 - Miscellaneous analog sensors with voltage output up to ± 10 volts or current loop output in any milliamp range, and with either linear or cubic calibration fits
- Special equations and soft channels can be programmed upon request (with sufficient lead time)
- Output types:
 - ASCII, time-stamped, tab-delimited file
 - Available on CD-R, DVD, or USB flash memory
 - Electronic file transfer to remote sites
- Output hardcopy data types:
 - Tabular printout (time history)
 - Channel to channel or time history plot containing up to 10 channels per plot

4.1.7 Bibliography

The following papers describe the arc jet facilities and some research programs performed in them at the Ames Research Center. The list is not exhaustive.

Current ARC arc jet facilities

Balboni, J.; and Adler, D.: Development and Operation of New Arc Heater Technology for a Large-Scale Scramjet Propulsion Test Facility. AIAA Paper 93-2786, presented at the 28th Thermophysics Conf., Orlando, Fla., July 1993.

Balboni, J.; Winovich, W.; and Balakrishnan, A.: Simulating AOTV Heating Environment in an Arc Jet. AIAA Paper 86-1312, presented at the AIAA/ASME 4th Joint Thermophysics and Heat Transfer Conference, Boston, Mass., June 1986.

Balter-Peterson, A.; Nichols, F.; Mifsud, B.; and Love, W.: Arc Jet Testing in NASA Ames Research Center Thermophysics Facilities. AIAA Paper 92-5041, presented at the Fourth Intl. Aerospace Planes Conf., Orlando, Fla., Dec. 1992.

Cox, J.; Winovich, W.; and Carlson, W. C.: A High-Voltage Isolated Automated Data Acquisition System. Instrument Soc. of Amer., 1976, ISA ASI 76211. In: Advances in Test Measurement, vol. 13: Proceedings of 22nd Intl. Instrumentation Symposium, Instrument Soc. of Amer., San Diego, Calif., May 1976, pp. 1–6.

Hightower, T. Mark; Balboni, John A.; Mac Donald, Christine L.; Anderson, Karl F.; Martinez, Edward R., "Enthalpy By Energy Balance for Aerodynamic Heating Facility at NASA Ames Research Center Arc Jet Complex," 48th International Instrumentation Symposium, The Instrumentation, Systems, and Automation Society (ISA), San Diego, CA, May 2002.

T. Gökçen, K. Skokova, J. A. Balboni, I. Terrazas-Salinas, and D. Bose, "Computational Analysis of Arc-Jet Wedge Calibration Tests in IHF 6-Inch Conical Nozzle," AIAA Paper 2009-1348, Jan. 2009.

T. Gökçen, G. A. Raiche, D. M. Driver, J. A. Balboni, and R. D. McDaniel, "Applications of CFD Analysis in Arc-Jet Testing of RCC Plug Repairs," AIAA Paper 2006-3291, June 2006.

T. Gökçen and D. A. Stewart, "Computational Analysis of Semi-elliptical Nozzle Arc-jet Experiments: Calibration Plate, Wing Leading Edge," AIAA Paper 2005-4887, June 2005, (published in AIAA Journal, Vol. 25, No. 1, 2007, pp. 128-137).

Winovich, W.; Balakrishnan, A.; and Balboni, J.: Experimental and Analytical Derivation of Arc Heater Scaling Laws for Simulating High-Enthalpy Environments of Aeroassisted Orbital Transfer Vehicle Application. AIAA Paper 85-1006, presented at the 20th Thermophysics Conf., Williamsburg, Va., June 1985.

Winovich, W.; and Carlson, W.: The Giant Planet Facility. 25th Intl. Instrumentation Symposium, Instrument Soc. of Amer., Anaheim, Calif., May 7–10, 1979.

Winovich, W.; and Carlson, W. C. A.: The 60 MW Shuttle Interaction Heating Facility. 25th Intl. Instrumentation Symposium, Instrument Soc. of Amer., Anaheim, Calif., May 7–10, 1979, pp. 59–75.

Thermal protection materials development in ARC arc jets

Leiser, D. B.; Churchward, R.; Katvala, V.; Stewart, D.; and Balter, A.: Advanced Porous Coating for Low-Density Ceramic Insulation Materials for Space Shuttle Thermal Protection Systems. Ceramic Engineering and Science Proceedings, vol. 9, Sept.–Oct. 1988, pp. 1125–1135.

Characterization of arc jet plasma flows

Babikian, D. S.; Park, C.; and Raiche, G. A.: Spectroscopic Determination of Enthalpy in an Arc Jet Wind Tunnel. AIAA Paper 95-0712, presented at the 33rd Aerospace Sciences Meeting, Reno, Nev., Jan. 1995.

Balboni, J. A.; Adler, D.; and Gokcen, T.: Measurement and Computation of Flow Properties in the NASA Ames 100 MW Direct Connect Arc Jet Facility Scramjet Combustor. AIAA Paper 95-0294, presented at the 33rd Aerospace Sciences Meeting, Reno, Nev., Jan. 1995.

Bamford, D. J.; O'Keefe, A.; Babikian, D. S.; Stewart, D. A.; and Strawa, A. W.: Characterization of Arc Jet Flows Using Laser-Induced Fluorescence. AIAA Paper 94-0690, presented at the 32nd Aerospace Sciences Meeting, Reno, Nev., Jan. 1994.

Gopaul, N. K. J. M.: Spectral Measurement of Nonequilibrium Arc Jet Free-Stream Flow. Paper presented at the 39th Intl. Instrumentation Symposium, Instrument Soc. of Amer., Albuquerque, N.M., May 1993.

Scott, C. D.: Survey of Measurements of Flow Properties in Arcjets. J. Thermophysics and Heat Transfer, vol. 7, no. 1, Jan.–Mar. 1993, pp. 9–24.

Sharma, S. P.; Park, C. C.; Scott, C.D.; Arepalli, S.; and Taunk, J.: Arcjet Flow Characterization. AIAA Paper 96-0612, presented at the 34th Aerospace Sciences Meeting, Reno, Nev., Jan. 1996.

History of ARC Arc Jet Facilities

Covington, M. A.; and Vojvodich, N. S.: Turbulent Flow Studies in Two Arc-Heated Duct Facilities. J. Spacecraft and Rockets, vol. 9, no. 6, June 1972, pp. 441–447.

Giannini, G. M.: The Plasma Jet. Scientific American, vol. 197, no. 2, Aug. 1957, pp. 80–88.

Shepard, C. E.; Ketner, D. M.; and Vorreiter, J. W.: A High Enthalpy Plasma Generator for Entry Heating Simulation. NASA TN D-4583, May 1968.

Shepard, C. E.; Watson, V. R.; and Stine, H. A.: Evaluation of a Constricted-Arc Supersonic Jet. NASA TN D-2066, Jan. 1964.

Shepard, C. E.; and Winovich, W.: Electric-Arc Jets for Producing Gas Streams with Negligible Contamination. ASME Winter Meeting: Plasma Jet Symposium, No. 61-WA-247, New York, N.Y., Dec. 1961. (NASA TM X-57090.)

Vorreiter, J. W.; and Shepard, C. E.: Performance Characteristics of the Constricted-Arc Supersonic Jet. Proceedings of the 1965 Heat Transfer and Fluid Mech. Inst., A. F. Charwat, ed.; Stanford University Press, June 1965, pp. 42–49.

4.2 Range Complex

The Range Complex comprises the Hypervelocity Free-Flight Facilities, the Ames Vertical Gun Range; and the Electric Arc Shock Tunnel.

4.2.1 Hypervelocity Free-Flight Facilities

The Hypervelocity Free-Flight Facilities at Ames Research Center currently include two active facilities: the HFF Aerodynamic Facility and the HFF Gun Development Facility. Both facilities were constructed in 1964 and are located in Building N-237. These are NASA's only aeroballistic facilities and two of a remaining, small handful that exist in North America.

4.2.1.1 Hypervelocity Free-Flight Aerodynamic Facility

The Hypervelocity Free-Flight Aerodynamic Facility is a combined Ballistic Range and Shock-Tube. The HFFAF consists of: a model launching gun (light-gas or powder); a sabot separation tank; a test section (with 16 orthogonal shadowgraph imaging stations); an impact/test chamber; a nozzle; and a combustion-driven shock tube (see figure 31). The primary purpose of the facility is to examine the aerodynamic and aero-thermodynamic characteristics and flow-field structural details of free-flying aeroballistic models. For this mode of traditional aeroballistic testing, each of the shadowgraph stations can be used to capture an orthogonal pair of images of a hypervelocity model in

flight along with its associated flow-field. These images combined with the recorded flight time history can be used to obtain various aerodynamic coefficients, including: CD , CLa , Cma , $Cmq + Cma$. In addition, a suite of visible ICCD and Infra-red cameras can be installed at various stations to record (via thermal imagery) surface temperature profiles of a model at various points during its flight. Such imagery can be used to infer such quantities of interests as heat transfer rates, and transition to turbulence locations. For very high Mach number (i.e. $M > 25$) simulation, models can be launched into a counter-flowing gas stream generated by the shock tube. This "counterflow" mode of testing tends to be both technically demanding and quite costly. The facility can also be configured for hypervelocity impact testing. In this mode, a light gas gun is typically used to launch impact particles (such as metallic spheres) at target materials mounted in the impact chamber or test section. A fourth mode of operation is shock tunnel testing. For this type of testing a fixed, instrumented model is mounted in either the impact/test chamber or at one of the shadowgraph stations in the test section. The combustion-driven shock tube is used to generate a short-duration reservoir of high-temperature, high-pressure test gas for expansion through the nozzle and over the test article. Most of the research effort to date has centered on Earth atmosphere entry configurations (Mercury, Gemini, Apollo, Shuttle, and CEV), planetary entry designs (Viking, Pioneer Venus, Galileo, and MSR), and aerobraking (AFE) configurations (see

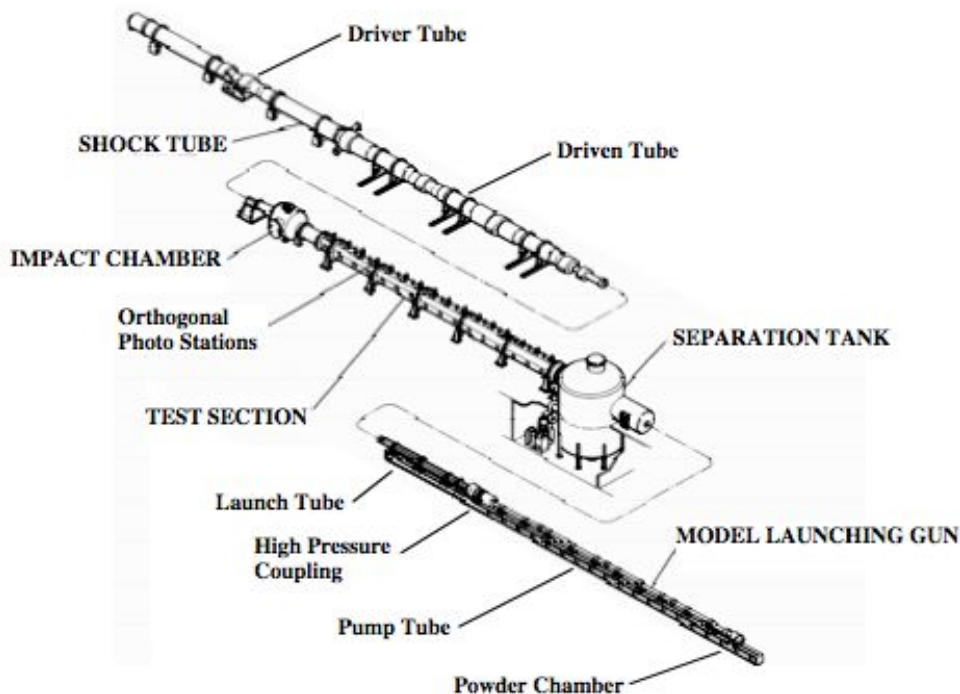


Figure 31. The Hypervelocity Free-Flight Aerodynamic Facility

figure 32). The facility has also been used for scramjet propulsion studies (NASP) and meteoroid/orbital debris studies (International Space Station, and RLV). What is truly unique about this facility is its ability to test at sub-atmospheric pressures and in test gases other than air.

4.2.1.1.1 Model Launching Guns

There is an extensive suite of model launching guns that are available for use in this facility. Included in this arsenal are four light-gas guns: 0.28 cal (7.1 mm), 0.50 cal (12.7 mm), 1.00 cal (25.4 mm), and 1.50 cal (38.1 mm). The size is designated by launch tube (barrel) diameter. A two-stage, light-gas gun typically consists of a powder chamber, pump tube, high pressure coupling, and launch tube (see figure 31). A deformable plastic piston is inserted into the upstream end of the pump tube. The sabot (which holds the model) is inserted into the launch tube breech, and a burst disk (diaphragm) is placed between the high pressure coupling and launch tube. The pump tube is evacuated and filled with a predetermined amount of hydrogen, and a gun powder charge is placed in the powder chamber. To launch the model, the gun powder charge is ignited. The resultant release of chemical energy accelerates the piston, compressing the hydrogen gas in the pump tube or first stage of the gun. At a predetermined pressure, the burst disk ruptures and the compressed hydrogen gas acts upon the base of the sabot, accelerating it down the launch tube or second

stage of the gun. When the sabot and model exit the launch tube, they enter the separation tank, wherein the sabot is stripped away from the model aerodynamically. The model passes through a small aperture, enters the test section, and ultimately impacts a wall of polyethylene in the impact chamber.

In addition to light-gas guns, the facility arsenal contains three powder guns: 0.79 cal (20 mm), 1.74 cal (44 mm), and 2.40 cal (61 mm). A powder gun is a simpler design and consists of a powder chamber and a launch tube. The launch package (sabot and model) is loaded into the launch tube breech, and a gun powder charge is placed in the powder chamber. To launch the model, the gun powder charge is ignited. The resultant release of chemical energy accelerates the launch package (sabot and model) down the launch tube and into the separation tank. The path from this point on is the same as for a light-gas gun.

The performance of the light-gas guns depends upon many, and sometimes conflicting, variables such as pump tube pressure, piston weight, gunpowder charge, burst disk (diaphragm) pressure rating and launch package weight. Theoretically, the maximum attainable velocity for each of the ARC guns is approximately 35,000 ft/s (10.7 km/s). However, a more realistic upper value is 28,000 ft/s (8.5 km/s) for robust models such as spheres and cylinders. For delicate aeroballistic models, maximum velocities are typically limited to 15,000 to 21,000

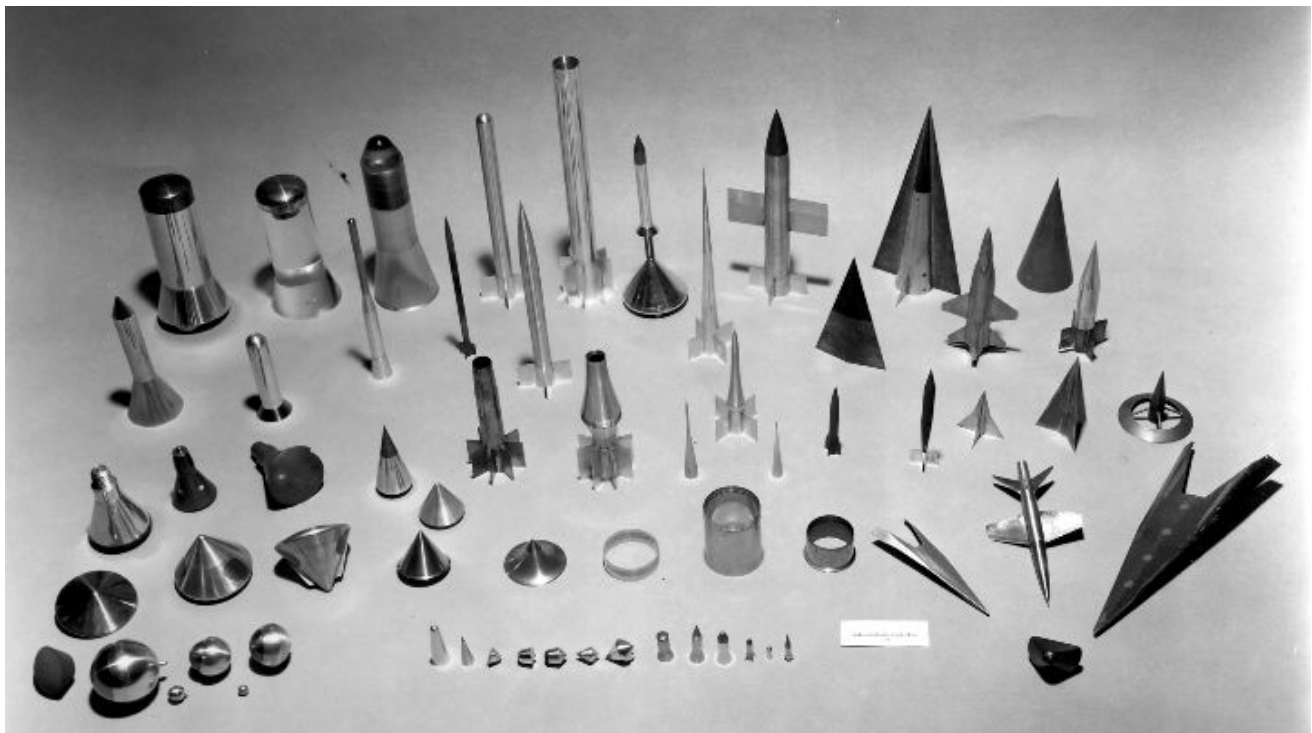


Figure 32. Examples of Aeroballistic Models

ft/s (4.5 to 6.5 km/s). Model diameters typically vary between 15 to 75% of the gun barrel diameter. Similarly, model masses typically vary from 0.01 to 100 grams. The lower limit velocity for each of the light-gas guns is approximately 6,500 ft/s (2 km/s). The ARC powder guns typically operate over a range of 1,000 to 8,000 ft/s (0.3 to 2.4 km/s).

4.2.1.1.2 Sabot Separation Tank

The sabot separation tank (also referred to as the dump tank) consists of a vertical cylindrical tank (approximately 4800 ft³ [140 m³]) with transition extensions on either side that are in line with the test section and the light-gas gun. Inside the dump tank and attached to the entrance of the test section extension is a large conical sabot stripper. This device has an adjustable aperture (0.5 to 7 in [1.3 to 17.8 cm] diameter) which allows model passage, while the conical structure deflects and ultimately stops the sabot pieces. A thin (typically ½ mil), mylar diaphragm can be placed inside the stripper device to isolate the test section from the dump tank. The gun extension includes an entry hatch. At the top of the dump tank, extending above the building roof, is a diaphragm port to limit internal pressures to approximately atmospheric. Overall length of the assembly is approximately 32 ft (10 m) and the volume (including the transition extensions) 5,100 ft³ (140 m³).

The associated vacuum pumping system is located below ground level adjoining the dump tank. The system consists of a pair of Stokes rotary pumps (300 cfm [140 L/s]), and a Roots-type booster pump (4,950 cfm [2,340 L/s] at 100 microns Hg [13 Pa] inlet pressure) which are attached to the test section transition extension. In addition to this, another pair of 300 cfm (140 L/s) rotary pumps are attached directly to the dump tank. Pressures of 50 microns Hg (7 Pa) are attainable in the test section, with leak rates of less than 10 microns Hg (1 Pa) per minute, despite the large numbers of windows and connections. Vacuum system valves are pneumatically operated and electrically controlled from the control room under the west end of the test section.

4.2.1.1.3 Test Section

The test section is 75 ft (23 m) long, with sixteen orthogonal shadowgraph stations spaced five feet apart. The octagonal cross-section is approximately 40 in (1 m) across the flats (at station 16) and is tapered (increasing as one moves towards station 1). The reason for this taper is to compensate for boundary-layer growth that occurs during shock tunnel flow conditions. Each shadowgraph station includes four windows (top, bottom and both sides). The window diameters are 12 in (30 cm) nominal for stations 1 through 9, and 15 in (38 cm) for stations 10 through 16. Window thicknesses are 1 in (2.5 cm) and 1.25 in (3.2 cm)

or 1.5 in (3.8 cm), respectively. At each station a shadowgraph can be taken in both the horizontal and vertical planes. Each view utilizes the following: A microsecond-duration spark light source mounted on the test section wall; A pair of spherical mirrors, with diameter to match the station window (the focal length is roughly 6 ft [2 m]), mounted on the facility walls; A 40 ns Kerr Cell shutter at the focal point of the second mirror; and a light-excluding box for mounting an 8×10 in (20×25 cm) sheet film holder. Other instrumentation on the test section includes the spatial reference system, halogen lamp w/photomultiplier tube model detectors, and ports on the upper diagonal surface of the test section wall at each station. These ports are used for vibration-isolated static pressure cell mountings, or as possible feed-through points for cables, gas supplies, thermocouples etc.

4.2.1.1.4 Impact/Test Chamber

The impact/test chamber is located between the test section and shock tube nozzle and has two primary roles. When the facility is operated as a ballistic range, a 2.5 in (6.4 cm) thick steel back stop plus a 24 in (61 cm) thick wall of polyethylene are installed at the nozzle exit to stop the aeroballistic models at the end of their flight. Similarly, hypervelocity impact targets can be mounted in the chamber for this mode of operation. When the facility is operated as a shock tunnel, the chamber can be used as a free-jet test cabin for mounting large, highly instrumented models. For this mode of operation, the steel and polyethylene wall is removed and diffuser panels are installed to smoothly redirect the shock tube flow into the test section. The impact/test chamber has numerous instrumentation feed-through ports, and four large access hatches (top, bottom, and both sides). Each hatch has two 15 in (38 cm) diameter windows to provide optical access if desired.

4.2.1.1.5 Nozzle

Attached to the shock tube side of the impact/test chamber is the Mach number 7 contoured nozzle (approximately 19 ft [5.8 m] long with an exit diameter of 39 in [99 cm]). The nozzle consists of five major components: a throat insert assembly which slides into the driven tube end-wall, and is connected to the nozzle trunnion by means of a Marmon clamp; the trunnion section which is mounted to a heavy foundation block (this fixes the longitudinal location of the entire test section); and three nozzle expansion sections, each of which are 62 in (160 cm) long. The nozzle insert assembly contains a thin mylar diaphragm which separates the initial driven tube and test section pressures. A variety of throats can be used to vary the area ratio between 80 and 300.

4.2.1.1.6 Shock Tube

A combustion driven shock tube is used to generate a reservoir of high-pressure, high-temperature test gas for expansion through the nozzle and test section. It consists of a driver or combustion tube (70 ft [20 m] long, 17 in [43 cm] inside diameter), and a driven tube (86 ft [26 m] long, 12 in [30 cm] inside diameter), (See figure 31.) The driver and driven tubes are initially separated by a flat, stainless-steel diaphragm with a thickness and score depth selected to provide self-break at a desired pressure. In a similar fashion, the driven tube and nozzle are separated by a thin Mylar diaphragm. The driver tube is filled with a combustible mixture (typically H_2 and O_2 along with He as a diluent); the driven tube is filled with the desired test gas (usually air); and the impact/test chamber (plus test section and dump tank) is evacuated to a low enough pressure to ensure proper flow establishment. To initiate the test flow, the combustible mixture is ignited by use of a hot-wire ignition system. When combustion nears completion, and the driver-tube attains a chosen critical pressure, the primary (stainless steel) diaphragm ruptures. As the heated, high-pressure driver gas (typically He and combustion products) begins to expand into the driven tube, the resulting pressure waves coalesce into a shock wave. The shock wave traverses the length of the driven tube, heating and pressurizing the test gas as it propagates. When the shock reaches the end of the driven tube, it reflects off the end-wall and breaks the Mylar diaphragm, thus establishing a relatively stable, high-temperature, high-pressure test gas reservoir. This reservoir, with enthalpy as high as 5,200 Btu/lbm (12,200 J/gm), typically persists for roughly 20 ms, as the flow passes through the nozzle and over the test object (mounted in the test cabin). During this time, various pressure, heat-transfer, and optical-diagnostic measurements can be recorded by the facility's data acquisition system (DAS).

The shock tube has been operated primarily in two combustion modes, heated-air ("slow-burn") or pseudo-stoichiometric ("fast-burn"). For the slow burn mode, the driver tube is filled with a mixture of 8 percent hydrogen and the remainder air. The mixture can be thermally stirred by passing a heating current through the ignition wire(s) prior to actually igniting the mixture. For the fast-burn mode, a nearly stoichiometric mixture of hydrogen and oxygen along with a sizable amount of diluent (usually helium and/or nitrogen) is used. The pressure in the driver tube rises by a factor of about 4 for slow burn and 8 for fast-burn.

The so-called "tailored operation" of the shock tubes is often used to produce essentially constant reservoir conditions for upwards of 20 milliseconds. The flow is typically near Mach 7 (based on area ratio), but temperature

and flow velocity may be varied jointly or discretely by changing nozzle throat size, and simultaneously adjusting the driver gas composition and driven tube fill pressure. This provides a great amount of flexibility in adjusting the total enthalpy, and effective Mach number. For example, the slow-burn mode can produce a 4,400 ft/s (1,300 m/s) flow at a static temperature of about 150° R (83 K), while fast-burn can yield flow velocities up to 12,000 ft/s (3,700 m/s) at temperatures approaching 694 K (1,250° R).

4.2.1.2 Hypervelocity Free-Flight Gun Development Facility

The HFF Gun Development Facility consists of: a light-gas gun; a sabot separation tank; an atmospheric test chamber; and a model catcher. This facility can be used to conduct gun performance enhancement studies wherein operational parameters and hardware configurations are adjusted/modified in an effort to increase maximum velocity (and/or launch mass capabilities), while maintaining acceptable levels of gun barrel erosion. The facility can also be configured to perform aerodynamic testing at atmospheric pressure. For this type of testing, an atmospheric test chamber that is 6.5'h × 6.5'w × 16'l (2m × 2m × 4.9m) and is equipped with multiple ICCD cameras (orthogonally oriented) along its length to provide a nearly unobstructed view of the entire model flight path is utilized. In 2004, this set up was used to launch simulated pieces of foam debris and record their trajectory. The high-fidelity-imagery records served as data needed to validate predictive codes as part of the Shuttle Return to Flight effort.

The facility operates in a manner similar to the HFFAF. The sabot and projectile exit the launch tube of the gun and enter a separation tank wherein the sabot is stripped away from the projectile either aerodynamically or using gun gases. The projectile passes through a small aperture, enters the atmospheric test chamber, and ultimately impacts a model catcher/target. As the model passes through the test chamber, pairs of orthogonally positioned ICCD cameras are used to capture multiple exposure images, which together provide a high-resolution record of the entire flight trajectory. The total flight path (from launch tube exit to impact) for this facility is 28 ft (8.5 m) as compared to 114 ft (34.7 m) for the HFFAF. The facility utilizes the same arsenal of light-gas guns and powder guns as the HFFAF (see section 4.2.1.1.1), plus a 1.0-cal (25.4 mm) air gun. With this arsenal of guns, models ranging in size from 1/16 in (1.6 mm) diameter to 2 in (50.8 mm) base diameter can be accelerated to velocities ranging from sub-sonic to hypersonic. Multiple, ballistic light screens are located within the test chamber and are used to detect model passage, trigger cameras and determine model velocity.

4.2.1.3 Bibliography

The following papers describe the Hypervelocity Free-Flight Facilities, their history, and some recent research programs performed in them at Ames Research Center. The list is not exhaustive.

- Berry, S. A., Chen, F-J, Wilder, M. C., and Reda, D. C., "Fundamental Hypersonics: Transition to Turbulence Experiments," AIAA 2007-4266, 39th AIAA Thermophysics Conference, Miami, FL, June 25-28, 2007.
- Bogdanoff, D. W.: Optimization Study of the Ames 0.5-inch Two-Stage Light-Gas Gun, NASA TM 110386 (1996).
- Bogdanoff, D. W., et. al.: Reactivation and Upgrade of the NASA Ames 16-Inch Shock Tunnel; Status Report, AIAA paper 92-0327, Reno, January 1992.
- Brown, J. D., Bogdanoff, D. W., Yates, L. A., and Chapman, G. T., "Free-Flight Dynamic Aero Data for a Lifting CEV Capsule," AIAA-2008-1232 46th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, Jan. 7-10, 2008.
- Brown, J. D., Bogdanoff, D. W., Yates, L. A., Wilder, M. C., and Murman, S. M., "Complex-Trajectory Aerodynamics Data for Code Validation from a New Free-Flight Facility," AIAA 2006-662, 44th AIAA Aerospace Sciences Meeting and Exhibit, January 2006.
- Brown, J., Yates, L., Bogdanoff, D., Chapman, G., Loomis, M., and Tam, T., "Free Flight Testing in Support of the Mars Smart Lander Aerodynamics Database," AIAA 2002-4410, AIAA Atmospheric Flight Mechanics Conference and Exhibit, Monterey, CA, Aug. 2002. (also as Journal of Spacecraft and Rockets, Vol. 43, No. 2, 2006, pp. 293 - 302.)
- Canning, T.N.; Seiff, A.; and James, C. S.: Ballistic Range Technology, AGARDograph No. 138 (1970).
- Cornelison, C. J.; and Watts, E. T.: Results of Two-Stage Light-Gas Gun Development Efforts and Hypervelocity Impact Tests of Advanced Thermal Protection Materials, NASA TM 112234 (1998).
- Cornelison, C. J.: Status Report for the Hypervelocity Free-Flight Aerodynamic Facility, paper presented at the 48th Aeroballistic Range Association Meeting, Austin TX, November 1997.
- Cornelison, C. J.: Development Update for the NASA Ames 16-Inch Shock Tunnel Facility, paper presented at the ISA 38th International Instrumentation Symposium, Las Vegas NV, April 1992.
- Reda, D. C., Wilder, M. C., Bogdanoff, D., and Prabhu, D. K., "Transition Experiments on Blunt Bodies with Distributed Roughness in Hypersonic Free Flight," Journal of Spacecraft and Rockets, Vol. 45, No. 2, March-April 2008, pp. 210-215.
- Reda, D. C., Wilder, M. C., Bogdanoff, D. W., and Olejniczak, J., "Aerothermodynamic Testing of Ablative Reentry Vehicle Nostip Materials in Hypersonic Ballistic-Range Environments," AIAA 2004-6829, 1st U. S. Air Force Developmental Test & Evaluation (DT&E) Summit, Woodland Hills, CA, November 16-18, 2004.
- Sanchez, G.; Westberry, R.; Christiansen, E.: International Space Station (ISS) Common Module, Node, and Cupola Windows Meteoroid and Orbital Debris (M/OD) Development Tests; Phase 1, Report JSC 27509, August 1998.
- Wilder, M. C., Reda, D. C., Bogdanoff, D. W., and Prabhu, D. K., "Free-Flight Measurements of Convective Heat Transfer in Hypersonic Ballistic-Range Environments," AIAA 2007-4404, 39th AIAA Thermophysics Conference, Miami, FL, June 25-28, 2007.
- Yates, L. A., Chapman, G. T., Bogdanoff, D. W., Brown, J. D., and Wilder, M. C., "Error Estimates of Aerodynamics Obtained in a New Type of Aeroballistic Facility," 56th Meeting of the Aeroballistics Range Association, NASA Johnson Space Center, Houston, Texas, October 2-6, 2005.

4.2.2 AVGR

The Ames Research Center Vertical Gun Range (AVGR) was designed to support scientific studies of impact processes during the Apollo missions. In 1979, it was established as a National Facility, funded through the Planetary Geology and Geophysics Program. In 1995, increased science needs across various discipline boundaries resulted in joint core funding by three different science programs at NASA Headquarters (Planetary Geology and Geophysics, Exobiology, and Origins Programs). In addition, the AVGR provides programmatic support for various proposed and ongoing planetary missions through special arrangements with the Facility Manager and Science Coordinator.

Ballistic technologies, utilizing light-gas guns, powder guns, and a pressurized air gun, enable acceleration of projectiles up to 7 km/s (23,000 ft/s). A truly unique feature of the AVGR is its ability to vary the gun axis or angle of elevation from horizontal to vertical, thus allowing impact angles from 0° to 90° with respect to the gravitational vector. This is particularly useful, and necessary, when studying crater formation processes. Figures 33 and 34 show a photograph and sketch of the Ames Vertical Gun Range Facility.

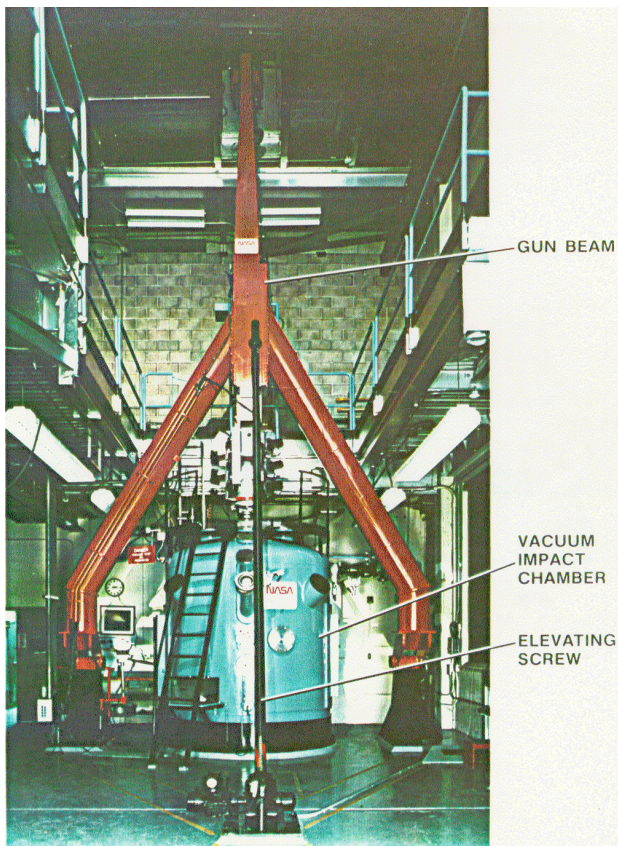


Figure 33. Photograph of the Ames Vertical Gun Range Facility

4.2.2.1 Model-Launching Guns

4.2.2.1.1 Light Gas Guns

For several decades the AVGR has utilized a .301-cal (7.5mm) light-gas gun to launch projectiles to velocities ranging from 2.5 to nearly 7 km/sec (8,200 to 23,000 ft/s). Recently (circa 2008) a .220-cal (5.6mm) and a .620-cal (15.7mm) gun were brought on-line to improve performance (consistency and accuracy) for certain particle sizes, and also to enable launching larger particles. All three guns use conventional smokeless powder to drive a plastic piston (pump piston) down the pump tube. This serves as a long-stroke, single compression of the hydrogen gas into a heavy-wall section called "high pressure coupling". Here the gas is raised to extreme pressure and temperature. A break valve in the high-pressure coupling, which initially seals the launch tube from the pump tube, then ruptures, and the propellant gas (hydrogen) drives the projectile down the launch tube. Typical launch capabilities are shown in figures 35 and 36.

4.2.2.1.2 Powder Gun

A .301-cal (7.5mm) powder gun is available that can propel models to velocities ranging from 0.5 to 3 km/s (1,600 to 9,800 ft/s). Figure 35 gives the performance envelope for this gun. It is worth noting that the powder gun is easier to use, cheaper to operate, and can produce more test rounds per day than the light-gas gun (i.e. 10 vs. 4). Therefore, it is to the experimenter's benefit to use this gun unless restricted by velocity considerations.

4.2.2.1.3 Pressurized Air Gun

For low-speed testing (below 1 km/s [3,300 ft/s] for model sizes up to 2.54 cm [1 in] diameter), a model-launching gun is available that uses compressed air in a small volume reservoir for the propelling gas. This gun represents an extremely inexpensive means of launching models, if low-speed impacts are desired. Performance capabilities for the air gun are indicated in figure 37.

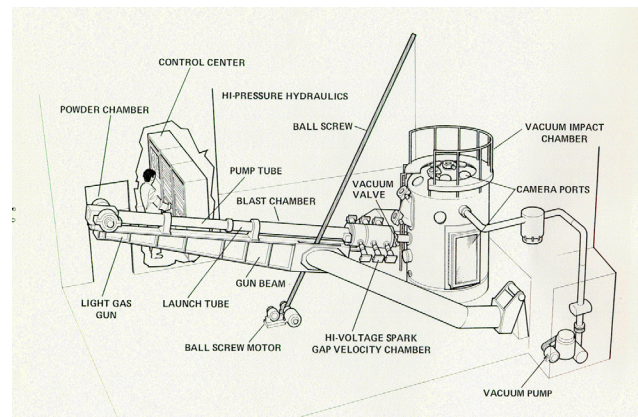


Figure 34. Sketch of the Ames Vertical Gun Range Facility

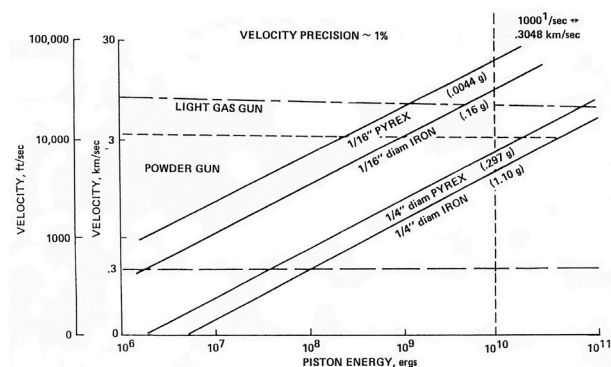


Figure 35. Typical gun performance

4.2.2.2 Projectiles and Sabots

The types of projectiles that can be launched include spheres, cylinders, irregular shapes, and clusters of many small particles. Projectiles can be metallic (i.e. aluminum, copper, iron), mineral (i.e. quartz, basalt), or glass (i.e. pyrex, soda-lime). For example, aluminum spheres can be launched individually for sizes ranging from 1.5 to 12.7mm (1/16 to 1/2 inch) in diameter; in groups of three for sizes ranging from 0.2 to 1.2mm; or as a cluster of many particles for sizes ranging from 2 to 200- μ m. In all of the guns, the projectiles are usually sabot (encased in a plastic carrier) to support and align them during their passage through the launch tube. This sabot is “stripped” away (via centrifugal force for all but the air gun) after exiting the launch tube, leaving the projectile(s) in free flight to the target. The types of projectiles that are most commonly used are spheres, and many standard size (spherical particle) sabots are in kept stock at the AVGR. Non-standard sizes and shapes can be accommodated. However, the experimenter must communicate his/her desired particle size and geometry, to the AVGR operational staff, well in advance of the test date to provide enough time for design and fabrication.

4.2.2.3 Velocity Chamber

The velocity chamber contains instrumentation and imaging equipment to measure projectile velocity and verify projectile integrity. Projectile passage is detected using laser line intervalometers and recorded with digital interval counters/timers. Projectile integrity is recorded via three spark-gap and film based shadowgraph imaging stations. As of April 2009, plans are under way to upgrade to a digital imaging system. The velocity chamber is shown in figure 38.

4.2.2.4 Impact Chamber

The target impact chamber is shown in figures 39 and 40. Experimental targets are contained within this 2.5-meter diameter vacuum chamber, which is capable of maintaining a reduced pressure of approximately 10^{-2} torr (1 Pa).

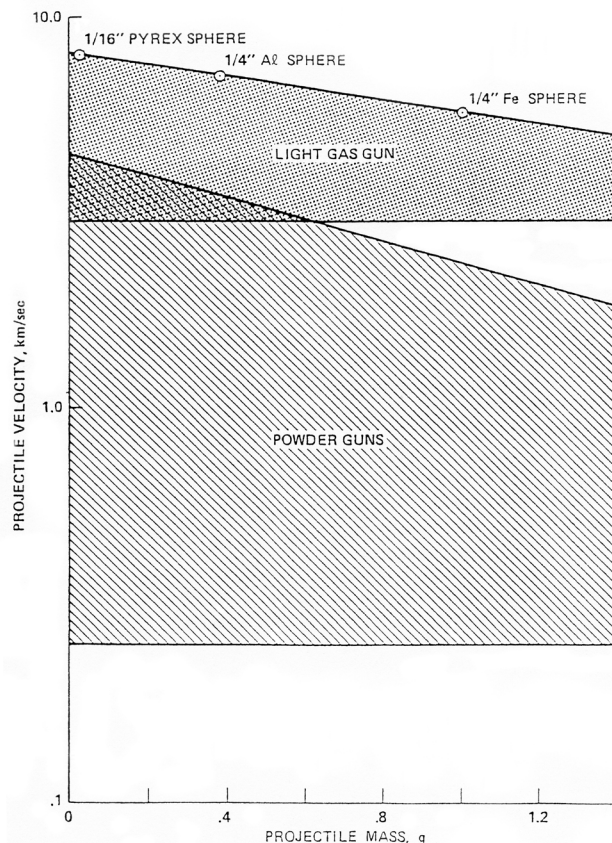


Figure 36. Light gas and powder gun performance

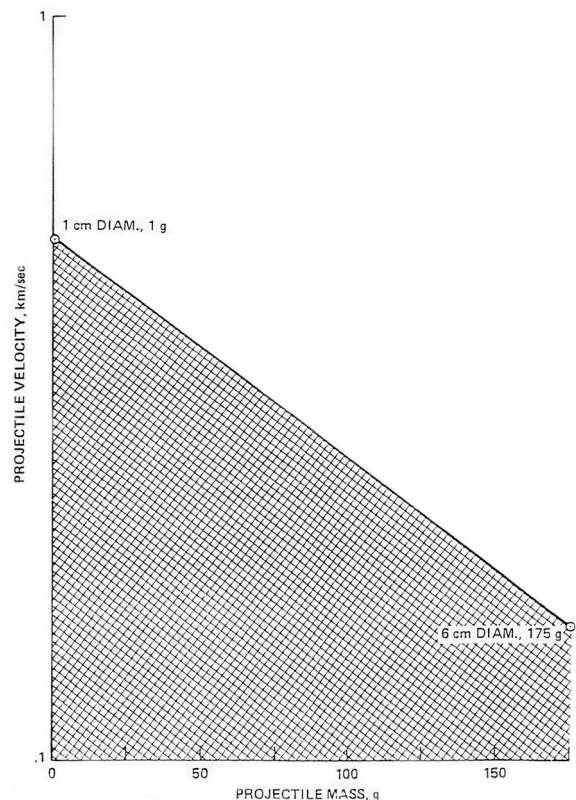


Figure 37. Air gun performance

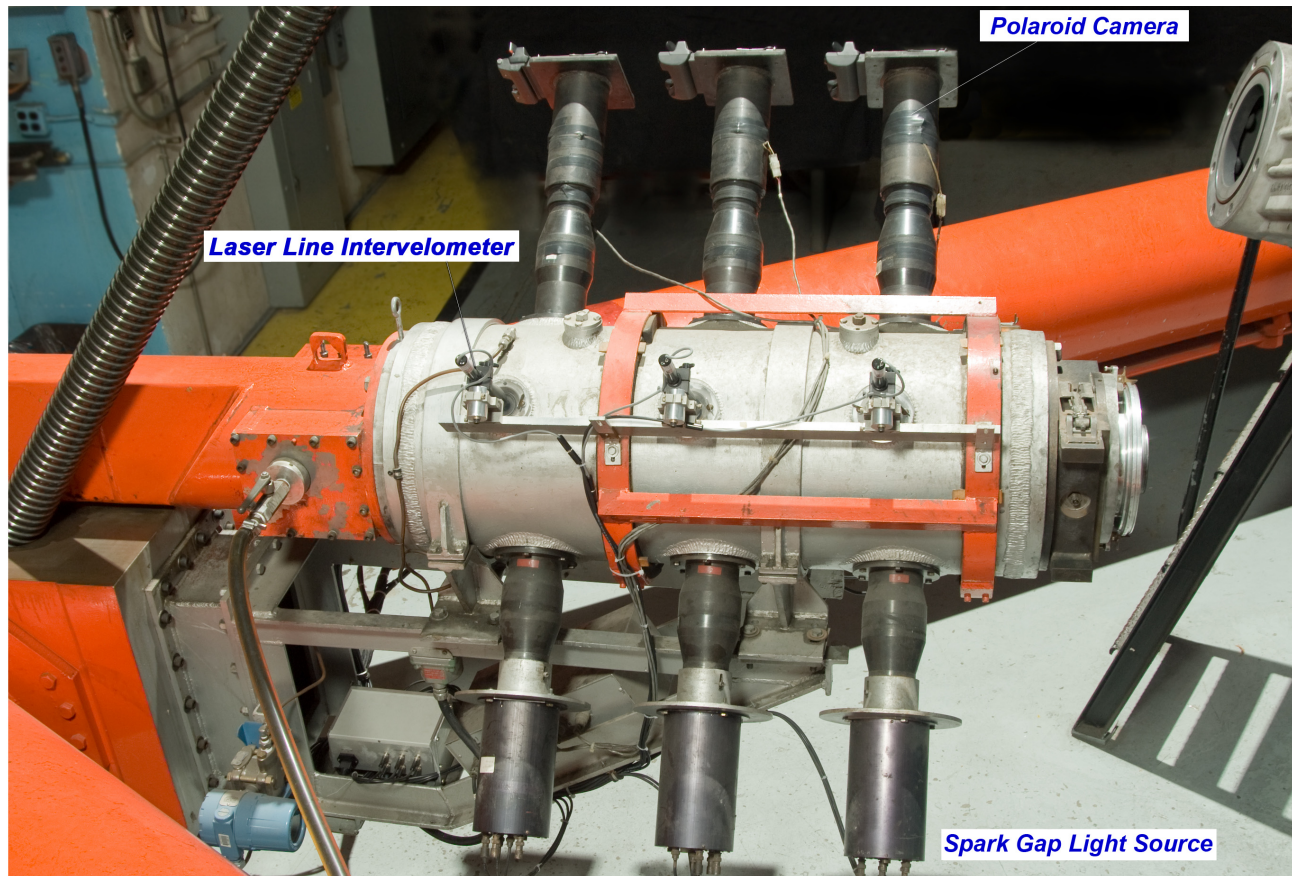


Figure 38. Photograph of the velocity measuring chamber

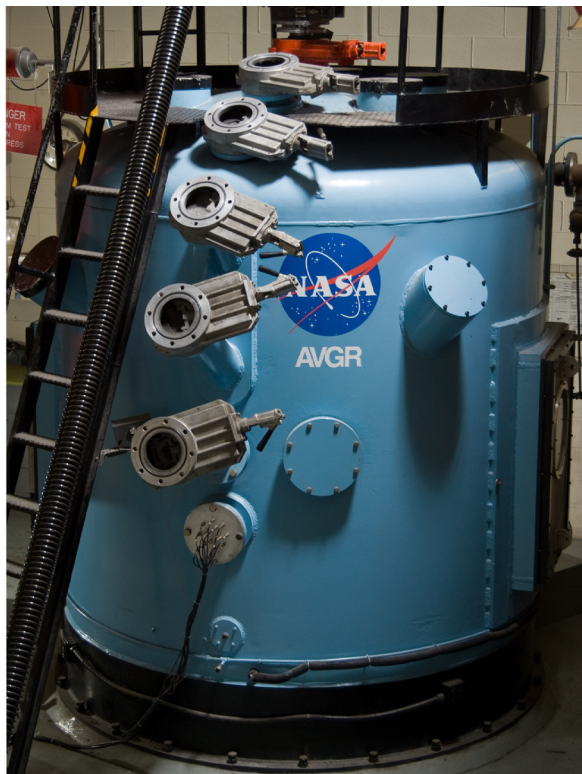


Figure 39. Impact vacuum tank (exterior view)



Figure 40. Impact vacuum tank (interior view)

Pump down rates and leak rates for this vacuum system are shown in figure 41. Targets are to be constructed in the standard target bucket, figure 42. Various target construction capabilities allow the placement of colored substrate to be used as markers to show crater formation. Targets can be either fixed within the chamber or they can be accelerated vertically to change the net gravitational effect during impact and crater formation. As is noted in the sketch of the vacuum impact chamber (figure 40) the model-launching gun can be positioned at various angles: seven positions at 15° intervals from 0° to 90°. Once again this allows varying the impact angle with respect to the gravitational vector. Instrumentation leads into the vacuum impact chamber are fed through the instrumentation plate provided. Figure 43 shows the connectors that are available.

4.2.2.5 Data Instrumentation

A programmable digital sequencer, located in the control room (101), is typically used to activate the AVGR and various instrumentation systems (see figure 44). This preset controller synchronizes the gun "fire" pulse, with the activation of various cameras, light sources, and trigger pulses for other instrumentation and devices during a test. A variety of high-speed digital imaging equipment can be used to accurately record the time history, and morphological evolutionary details, of impact and crater formation processes. This equipment includes: a pair of Vision Research, Phantom V10 cameras; a pair of Phantom V12 cameras; and a pair of Shimadzu HPV-1 cameras. Both Phantom camera types are color, can be operated over a wide range of framing rates, exposure times, resolution levels, variable aspect ratios (image sizes), and extensive record lengths (i.e. over 1 second at maximum frame rate and resolution). The V10 units

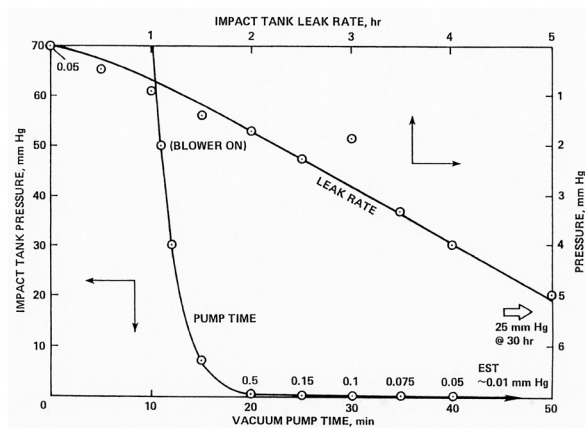


Figure 41. AVGR vacuum system performance

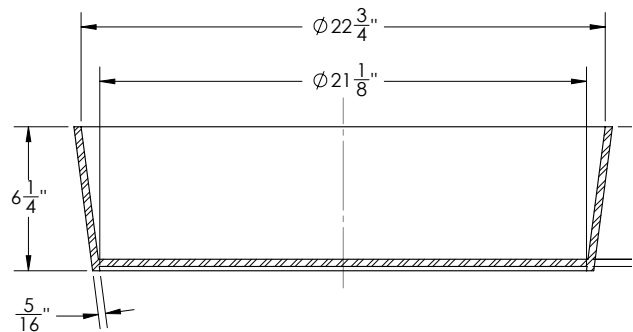
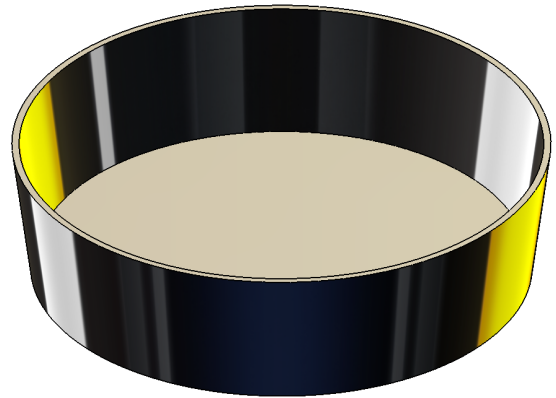


Figure 42. Ames standard bucket dimensions

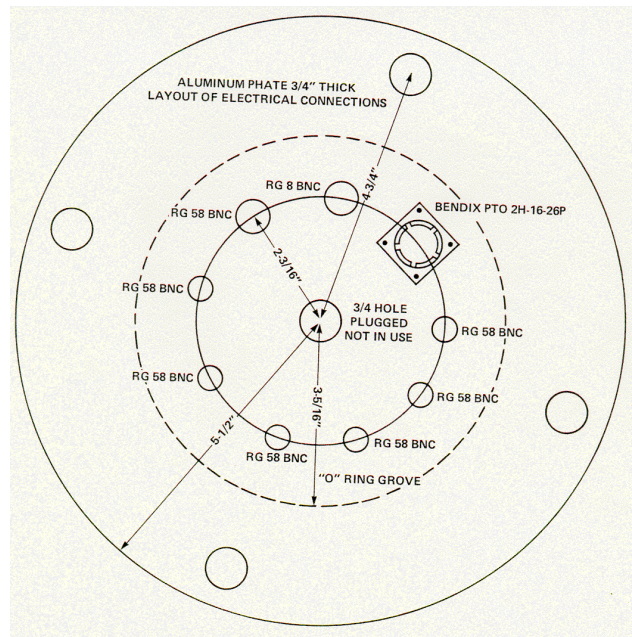


Figure 43. AVGR standard vacuum feed-through plate

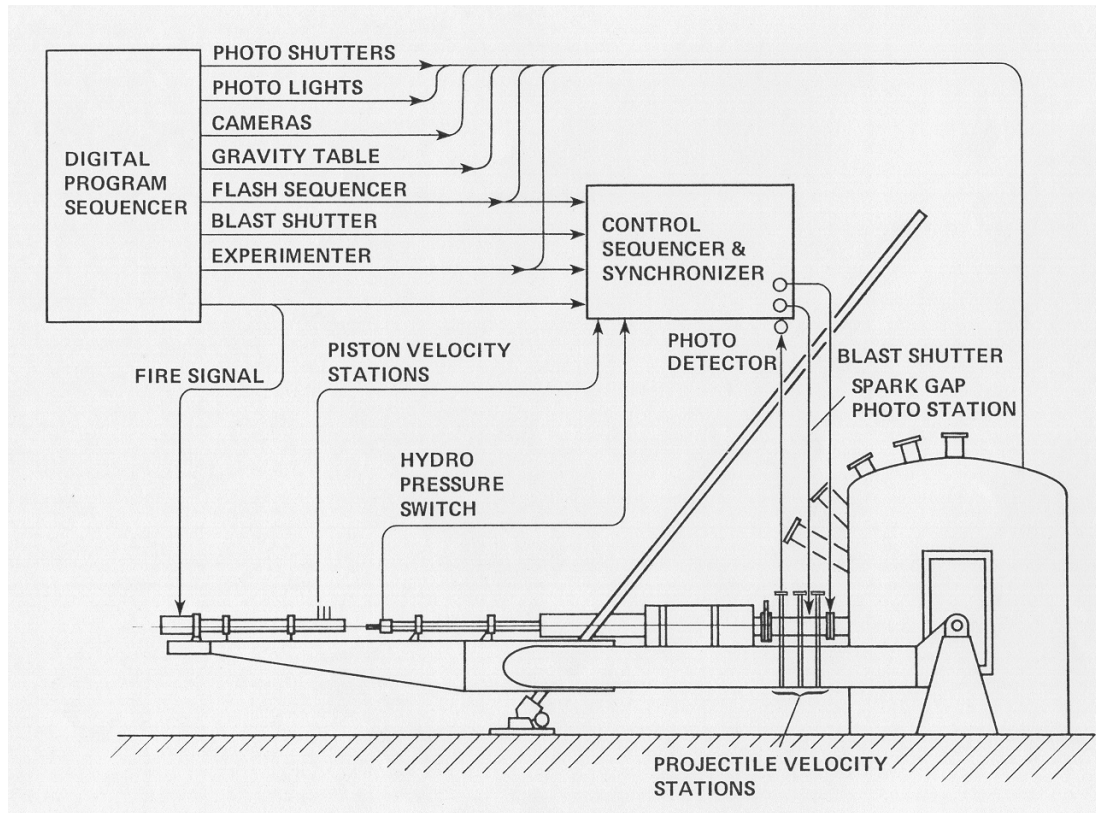


Figure 44. AVGR simplified block diagram

are 14 bit devices and are particularly well suited for, yet not limited to, framing rates up to 10,000 fps. Likewise the V12 units are 12 bit devices and are well suited for framing rates ranging from 10,000 to 50,000 fps (yet they can go as high as 1,000,000 fps). The Shimadzu cameras are 10 bit devices, monochromatic, and maintain an image size of 312 x 260 pixels and a record length of 102 frames for all framing rates (up to 1,000,000 fps). Note: data files from all of the camera systems are delivered to the Principal Investigator (researcher) in either .avi or stacked .tiff format. In addition, a suite of interval timers that are accurate to within 10 nanoseconds are used to record projectile time of arrival information (generated by the velocity chamber projectile detection equipment). Instrumented targets can be readily accommodated using the standard vacuum feed-thru plate. Lastly, oscilloscopes and spectrographic equipment can be accommodated through special arrangement with the Science Coordinator and Facility Manager.

4.2.2.6 Office Space

Building N-204A houses the AVGR and the offices of the operational crew (i.e. site leader, technicians and imaging technologist). Additional office space within this building is available for both the current and future Principal Inves-

tigators. There is, in addition, a complete machine shop with welding facilities and a target preparation room.

4.2.2.7 Subsystems

The Ames Vertical Gun Range consists of the following systems.

4.2.2.7.1 Gun Elevation System

The gun elevation system is used to raise the gun and align it with the various impact chamber ports. The elevation system includes: the gun mounting beam and hinge assembly; the elevation ball-screw; the ball-screw drive-motor; and the associated control pendant. A photograph of this system is shown in figure 45.

4.2.2.7.2 High Pressure Hydraulics Systems

The high-pressure hydraulic system is used to pressurize the clamping mechanism within the high-pressure coupling. This mechanism is used to maintain a leak tight seal between the coupling and the launch tube. The system consists of a hydraulic pump and hose plus a pneumatic supply and actuator.

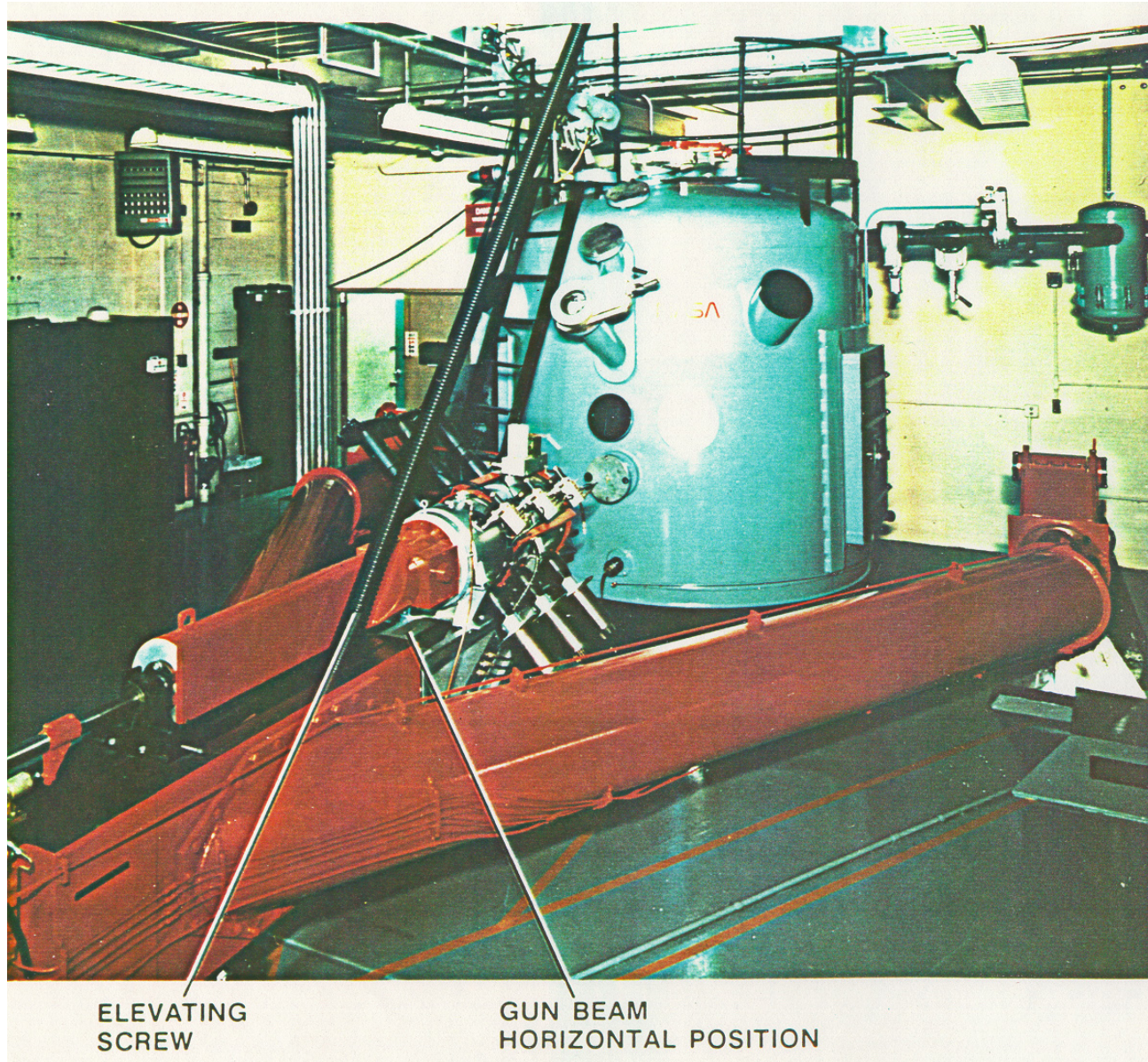


Figure 45. Photograph of gun elevation system, beam in horizontal position

4.2.2.7.3 Light-Gas Gun Loading System

The LGG gas loading system is used to pressurize the pump tube. The system consists of a control panel and its assortment of valves and gauges, hydrogen and helium cylinders (located in a protected enclosure outside N204A), and the associated high-pressure tubing, hoses etc. Helium is used to purge and leak check the pump tube prior to filling with hydrogen.

4.2.2.7.4 Impact Chamber Gas Loading System

The impact chamber gas loading system is used to fill the impact chamber with gases other than air. This capability

is most often utilized to simulate non-earth atmospheric environments. The system consists of: a small control panel (located near the impact chamber) and its various valves; gas cylinders such as nitrogen, helium, argon and carbon dioxide (located outside N204A); and the associated high-pressure tubing system.

4.2.2.7.5 Data Acquisition System

The data acquisition system consists primarily of cameras, velocity counters, and timing/triggering subsystems. The cameras typically used are: (a) Phantom V-10 cameras for frame rates up to 10,000 fps; (b) Phantom V-12 cameras for frame rates up to 50,000 fps; and (c) Shimadzu

cameras for frame rates up to 1,000,000 fps. Note, the Phantom cameras can be operated at higher frame rates with lower resolution.

4.2.2.7.6 Vacuum System

There are two vacuum systems that support the operation of the AVGR, one for the gun itself and one for the impact chamber. For the gun, a small (Welch) mechanical (rotary) pump and its associated valves, fittings and lines is used to evacuate the pump tube to 1 torr or less. For the impact chamber two larger capacity, rotary pumps plus a "roots" type blower are used to achieve vacuum levels of 0.03 torr or less. A large, 26 × 40 in (66 × 100 cm) glass viewing window is located on one side of the chamber, plus several smaller ports at various locations, to provide numerous viewing angles.

4.2.2.7.7 Gunpowder Storage and Charge Preparation Area

The gunpowder storage and charge preparation area is cipher lock secured and located within the AVGR control room (101). It is used to store limited amounts (up to 50-lbs. net explosive weight) of smokeless powder, rounds, primers, and electro-explosive devices (EED's). It also serves as a powder weighing and charge preparation workshop in accordance with NASA Explosives Safety Regulations. The floor is covered with conductive plastic sheeting and all bench tops and cabinets are electrically bonded and grounded. Access to this room is controlled by the Ballistic Range Facility Staff, and occupancy is restricted to a maximum of one person at any time. Eye

protection (either safety glasses or face shield) is required when preparing explosive devices within this room. In addition, to prevent static charge buildup and possible spark discharge during the assembly of devices containing explosives, all personnel are required to wear grounding wrist straps and cotton clothing while performing these activities. The integrity of the wrist strap must be verified with the testing device prior to any charge preparation activities. All personnel who handle and/or transport explosives are trained in accordance with NASA and Ames requirements.

4.2.2.7.8 Control Room

The AVGR control room is located in room 101 in Building N204A. Firing of the gun and activation of the instrumentation is controlled from this location. The control system equipment is mounted in three equipment racks. The center rack contains the digital sequencer, igniter tester, various indicator displays, and the firing control panel. The left rack contains the interval timers, the start pulse generator, a digital oscilloscope, and can accommodate various test specific devices. The right rack contains the power supplies, amplifiers and displays for the projectile detection and imaging equipment. It should be noted that no personnel are allowed in the gun room (102) or test area (201) during firing operations. Also, only AVGR staff members are allowed in the control room during this time, unless special arrangements are made with the Facility Manager.

4.2.2.8 Bibliography

The following papers illustrate some of the research performed in the AVGR. This list is by no means exhaustive, nor does it include numerous abstracts or PhD theses.

- Anderson, J. L. B. and Schultz P. H. (2006), Flow-field center migration during vertical and oblique impacts, *International Journal of Impact Engineering* 33, 35-44.
- Anderson, J. L. B., Schultz, P. H., and Heineck, J. T. (2004), Experimental Ejection Angles: Implications for the Subsurface Flow Field during Oblique Impacts, *Meteorites and Planetary Science* vol. 39, 303-320.
- Anderson, J. L. B.; Schultz, Peter H.; Heineck, James T. (2003), Asymmetry of ejecta flow during oblique impacts using three-dimensional particle image velocimetry. *J. Geophys. Res.* Vol. 108, No. E8, 5094, 10.1029/2003JE002075.
- Anderson, W. and Ahrens, T.J. 1994. Physics of Interplanetary Dust Capture Via Impact Into Organic Polymer Foams. *J. Geophys. Res.*, 99, 2063-2071.
- Barnouin-Jha, O.S., Schultz, P.H. and Lever, J. (1999), Investigating the interactions between an atmosphere and an ejecta curtain: I. Air flow experiments, *J. Geophys. Res.*, 104, (E11), 27,105-27-116.
- Barnouin-Jha, O. and Schultz, P.H. 1998. Lobateness of impact ejecta deposits from atmospheric interactions, *J. Geophys. Res.*, 103, 25,739-25,756.
- Barnouin-Jha, O. and Schultz, P.H. 1996. Impact-generated Vortices: Theory and Experiments, *J. Geophys. Res.*, 101, 21,099-21,115.
- Bunch, T.E., Schultz, P.H., Cassen, P., Brownlee, D., Podolak, J., Lissauer, J., Reynolds, R., and Chang, S. 1991. Are some chondrite rims formed by impact processes? Observations and experiments. *Icarus* 91, p.76-92.
- Bunch, T.E., Radicati, F., Fleming, R., Harris, D., Brownlee, D., and Reilly, T.W. 1991. LDEF Impact Craters Formed by Carbon-Rich Impactors: A Preliminary Report, Proc., First LDEF Post-Revival Sym., NASA CP-3134, 549-563.
- Bunch, T.E., Becker, L., Bada, J., Macklin, J., Radicati di Brozolo, F., Fleming, R.H., and Erlichman, J. 1993. Hypervelocity Impact Survivability Experiments for Carbonaceous Impactors, Proc. Second LDEF Sym., NASA CP 3194, 453-478.
- Crawford, D. A., and Schultz P. H. (1999), Electromagnetic properties of impact-generated plasma, vapor and debris, *Int. J. Impact Eng.*, 23, 169-180.
- Crawford, D.A. and Schultz, P.H. 1993. The Production and Evolution of Impact-generated Magnetic Fields. *International J. Impact Eng.*, 14, 205-216.
- Crawford, D.A. and Schultz, P.H. 1991. Laboratory investigations of impact-generated plasma. *J. Geophys. Res.*, 96, No. E3, 18,807-18,817.
- Crawford, D.A. and Schultz, P.H. 1988. Electromagnetic emissions from oblique hypervelocity impacts. *Nature* 336, 50-52.
- Dahl, J. M. and P. H. Schultz (2001), Measurement of stress wave asymmetries in hypervelocity projectile impact experiments, *Proceedings of the 2000 Hypervelocity Impact Symposium (HVIS)*, *Int. J. Impact Eng.* 26, 145-155.
- Davis, D. and Ryan, E. 1990. On Collisional Disruption: Experimental Results and Scaling Laws. *Icarus*, 83, 156-182.
- Domínguez, G., Westphal, A. J., Jones, S. M., Phillips, M. L. F. (2004), Fluorescent Impact Cavities in a Titanium Doped Al₂O₃-SiO₂ Aerogel: Implications for the Velocity Resolution of Calorimetric Aerogels. *Journal of Non-Crystalline Solids*, v. 350C pp 385-390.
- Domínguez, G., Westphal, A. J., Phillips, M. L. F., Jones, S. M. (2003), A Fluorescent Aerogel for Capture and Identification of Extraterrestrial Dust, *The Astrophysical Journal*, v. 592, pgs. 631-635.
- Durda, D. D., G. J. Flynn, and T. W. VanVeghten (2003), Impacts into porous foam targets: Possible implications for the disruption of comet nuclei, *Icarus* 163, 504-507.
- Durda, D. D. and G. J. Flynn (1999), Experimental study of the impact disruption of a porous, inhomogeneous target. *Icarus* 142, 46-55.
- Ernst, C.M. and Schultz, P.H. (2007) Evolution of the Deep Impact flash: Implications for the nucleus surface based on laboratory experiments, *Icarus*, doi:10.1016/j.icarus.2007.03.030.
- Flynn, G. J., D. D. Durda, L. E. Sandel, J. W. Kreft, and M. M. Strait (2008), Dust production from the hypervelocity impact disruption of the Murchison hydrous CM2 meteorite: Implications for the disruption of hydrous asteroids and the production of interplanetary dust. *Planetary and Space Science* (in press).

- Flynn, G. J., and Durda, D. D (2004), Chemical and mineralogical size segregation in the impact disruption of inhomogeneous, anhydrous meteorites, *Planetary and Space Science* 52, 1129–1140.
- Griffiths, D.J., Buettner, D.J., and Tsou, P. 1991. Effect of Void-Size Distribution on the Hugoniot State at Low Shock Pressures. *J. Appl. Phys.*, 70, 4790-4796.
- Heineck, J. T., P. H. Schultz, and J.L.B. Anderson (2003), Application of Three-component PIV to the Measurement of Hypervelocity Impact Ejecta, *Jrnl. Visualization*, Vol 5, No. 3, pp 233-241.
- Melosh, H.J., Ryan, E.V., and Asphaug, E. 1992. Dynamic Fragmentation in Impacts: Hydrocode Simulation of Laboratory Impacts. *J. Geophys. Res.* 97, p.14735-14759.
- Minitti, M., Rutherford, M. J., Taylor, B. E., Dyar, M. D., and Schultz, P. H. (2007), Assessment of shock effects on amphibole water contents and hydrogen isotope compositions: 1. Amphibole experiments. *Earth and Planet. Sci. Letts.* Vol. 266, Issue 1-2, p. 46-60.
- Podolak, M., Prialnik, D., Bunch, T.E., Cassen, P. and Reynolds, R. 1993. Processing of Refractory Inclusions (CAIs) in Parent Body Atmospheres-II, *Icarus*, 104, 97-109.
- Radicati di Brozolo, F., Bunch, T.E., Fleming, R.H., and Macklin, J. 1994. Fullerenes in an Impact Crater on the LDEF Spacecraft, *Nature*, 369, 37-40.
- Rietmeijer, F. J. M., P. H. Schultz, and T. E. Bunch (2003) Carbon Calabashes in a Shock-produced Carbon Melt, *Chemical Physics Letters* 374(5/6), 464-470.
- Ryan, E. V., Davis, D. R., and Giblin, I., (1999), A Laboratory Impact Study of Simulated Edgeworth-Kuiper Belt Objects, *Icarus*, Volume 142, Issue Icarus, pp. 56-62
- Ryan, E.V., Hartmann, W.K., Davis, D.R. 1991. Impact Experiments: Catastrophic Fragmentation of Aggregate Targets and Relation to Asteroids. *Icarus*, 94, 283-298.
- Schultz, P. H., Eberhardy, C. A., Ernst, C. M., A’Hearn, M. F. A., Sunshine, J. M., Lisse, C. M. (2007), The DI oblique cratering experiment, *Icarus* 190, 295-333.
- Schultz, P. H., Eberhardy, C. A., Ernst, C. M., A’Hearn, M. F. A., Sunshine, J. M., Lisse, C. M. (2007), The DI oblique cratering experiment, *Icarus* 190, 295-333.
- Schultz, P. H. and J. F. Mustard (2004), Impact melts and glasses on Mars, *J. Geophys. Res.*, vol.109, E01001, doi: 10.1029/2002JE002025.
- Schultz, P.H. 1996. Effect of impact angle on vaporization. *J. Geophys. Res.*, 101, 21,117-21,136.
- Schultz, P.H. 1993. Impact Crater Growth in an Atmosphere. *International J. Impact Eng.*, 114, 659-670.
- Schultz, P.H. 1992. Atmospheric effects on ejecta emplacement and crater formation on Venus from Magellan. *J. Geophys. Res.*, 97, No. E10, 16,183-16,248.
- Schultz, P.H. 1992. Atmospheric effects on ejecta emplacement. *J. Geophys. Res.*, 97, E7, 11,623-11,662.
- Schultz, P.H. 1992. Atmospheric effects on cratering efficiency. *J. Geophys. Res.*, 97, E1, 975-1006.
- Schultz, P.H. and Gault, D.E. 1990. Prolonged global catastrophes from oblique impacts. In V.L. Sharpton and P.D. Ward, eds., *Global Catastrophes in Earth History: An Interdisciplinary Conference on Impacts, Volcanism, and Mass Mortality*, Geological Society of America Special Paper 247, 239-261.
- Sugita, S. and P. H. Schultz (2003a), Interactions between impact-induced vapor clouds and the ambient atmosphere: 1. Spectroscopic observations using diatomic molecular emission. *J. Geophys. Res.*, Vol. 108, (E6), 5051, doi: 10.1029/2002JE001959.
- Sugita, S., Schultz, P.H., and Adams, M.A. 1998 Spectroscopic measurements of vapor clouds due to oblique impacts, *J. Geophys. Res.*, 103, 19,427-19,441.
- Tsou, P. 1990. Intact Capture of Hypervelocity Projectiles. *Int. J. Impact Engng*, Vol. 10, 615-627.
- Tsou, P. and Griffiths, D.J., 1993. Exploratory investigations of hypervelocity intact capture spectroscopy. *Int. J. Impact Energy*, 14, 751-761.

4.2.3 EAST Facility

The Electric Arc-driven Shock-Tube Facility at NASA Ames Research Center is a high enthalpy shock tunnel, shown schematically in figure 46. It creates a high-velocity stream of test gas that is large enough for detailed model studies, but of short duration. The design reservoir enthalpy is 29 kJ/g (12,400 btu/lb_m) (equivalent stream velocity of 7.6 km/s [25,000 ft/s]). A reflected shock reservoir with a tailored-interface restriction allows for a range of reservoir enthalpies.

4.2.3.1 Capacitor Bank

Energy to the driver is supplied by a 1.24 MJ, 40 kV capacitor energy-storage system. The six-tier capacitor bank has 220 capacitors. By using different combinations of series-parallel connections, the capacitance of the bank can be varied from 149 μ F to its maximum value of 6,126 μ F (1,530 μ F for 40-kV operation). Nominal total system inductance exclusive of the load (arc) is 0.26 μ H, and the resistance is 1.6 m Ω .

4.2.3.2 Collector Assembly and Discharge Chamber

The current collector and arc chamber are shown schematically in figure 47. The collector ring consists of two coaxial copper cylinders. The outer cylinder is flanged to the driver tube and is electrically grounded; the inner cylinder is connected by a copper spring contact plate to the main electrode. The high-voltage electrode has a hollow core through which a rod extends back to the piston of a pneumatic solenoid (air cylinder). The solenoid actuates the trigger. Several different materials have been used for the trigger wire, but most of the tests have been made with tungsten wire. The trigger wire is coiled along the length of the arc chamber to the ground plate. When the slack wire is drawn to the high-voltage electrode, the current flow is initiated. The thermionic emission from the trigger wire helps initiate the arc discharge.

The arc chamber is designed for a pressure of 1000 atm (100 MPa) and fabricated of a nonmagnetic stainless steel in two sections. An insulating liner of filament-wound fiberglass with a bonded inner layer of silicone rubber forms the inner wall of the chamber. This liner is surprisingly durable and can be reused many times; techniques have been developed to replace the rubber inner layer as often as required.

4.2.3.3 Driver Tube

The arc-heated driver tube can be viewed as an energy convertor, changing electrical energy into pressure and temperature, and serves as the connecting link between the energy source and the test-gas accelerator.

The driver configuration is a 17.7-cm conical drive configuration with a 10.16 cm (4 in) exit (driver volume = 632 cm³ [39 in³]).

4.2.3.3.1 Primary Diaphragm

The diaphragm is made of mylar 0.35 to 0.50 mm (0.013 to 0.019 in) or aluminum foil (0.012 to 0.35 in) in thickness. It is ruptured due to the rise in pressure within the driver during the arc discharge. There is a time lag of 20 to 40 μ s between the instant that the breaking pressure is reached (approximately 11.5 atm [1.2 MPa] for a 0.35 mm [0.013 in] diaphragm) and the diaphragm is fully open.

4.2.3.4 Shock Tube

The design of the shock-tube portion of the facility, as with the driver chamber, is predicated upon its use to develop a reflected-shock reservoir of test gas of sufficient quantity and duration to supply a large supersonic nozzle.

The facility consists of one driver system and two parallel driven tubes: one is a 10 cm (4 in) ID tube 12 m (40 ft) in length made of aluminum; the other is a 60 cm (24 in) ID tube 21 m (69 ft) in length made of stainless steel.

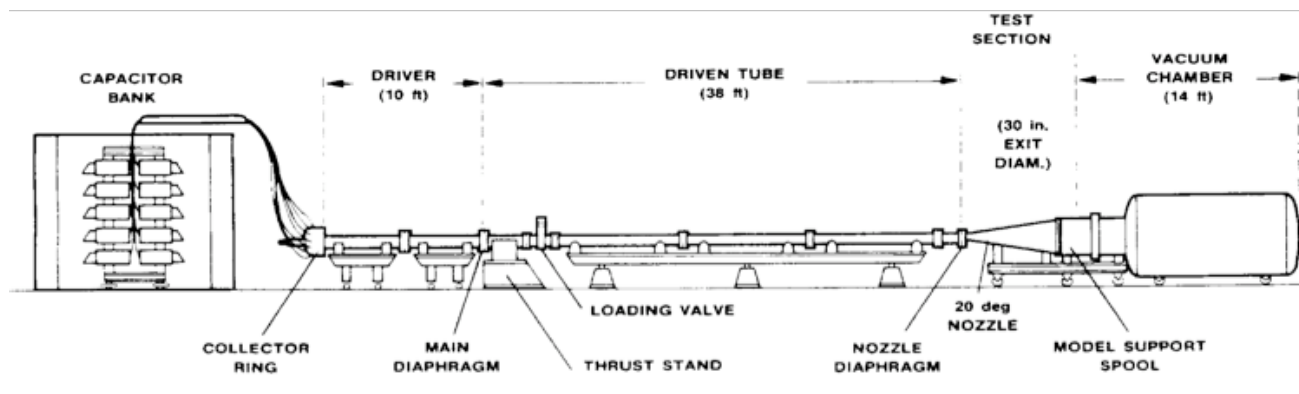


Figure 46. Schematic diagram of the EAST Facility

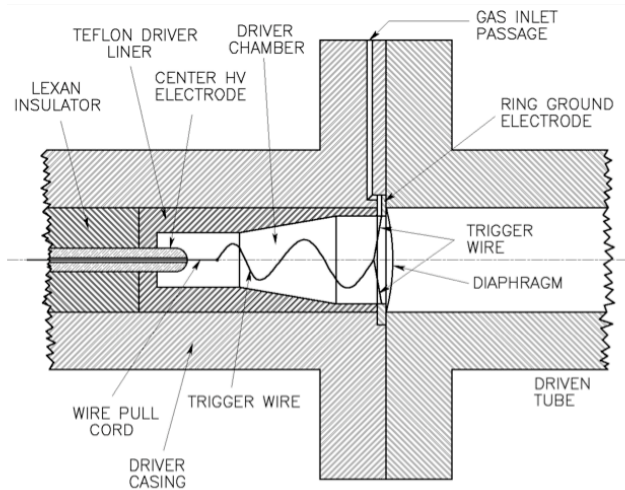


Figure 47. EAST Facility current collector and arc chamber

The driven tube is shown in figure 48 along with other components of the facility. Marked on the image are the location of the various diagnostic ports. The inset depicts the test section. On either side of the test section are the upstream and downstream portions of the driven tube. Several ports on the upstream section are used for monitoring the shot, while the downstream portion is mostly unused. Available round ports are labeled by letters in alphabetical order starting from the port closest to the driver section. The labels each represent one axial location along the length of the tube. In most cases, there are

two ports on opposite sides of the tube at each location. Exceptions are ports F, G, H, I, K, M, O, Q which have four locations, 90 degrees apart and ports L and P which have only one location. Port A is occupied on the west side by the gas loading valve and port D is occupied on the east side with the pressure port.

4.2.3.4.1 Upstream

The upstream section has 6 port locations available, two of which are occupied by the gas loading valve and facility pressure gauges. The remaining ports may accommodate pressure sensors or observation windows. Different holders exist for the pressure sensors and observation windows and the design of these holders differ from the holders used in the test section.

4.2.3.4.2 Test Section

The test section has 30 round diagnostic ports and 2 rectangular slot (long) window ports. The ports consist of primary and secondary inserts, between which is mounted either a window or pressure sensor holder. Some ports, being unused at present, have a single blank in place of the primary/secondary arrangement. The primary inserts are installed within the tube with intention of seldom being removed.

4.2.3.4.3 Vacuum System

There are two primary pumping stations, denoted 1 & 2. At each station a facility (poppet) valve isolates the

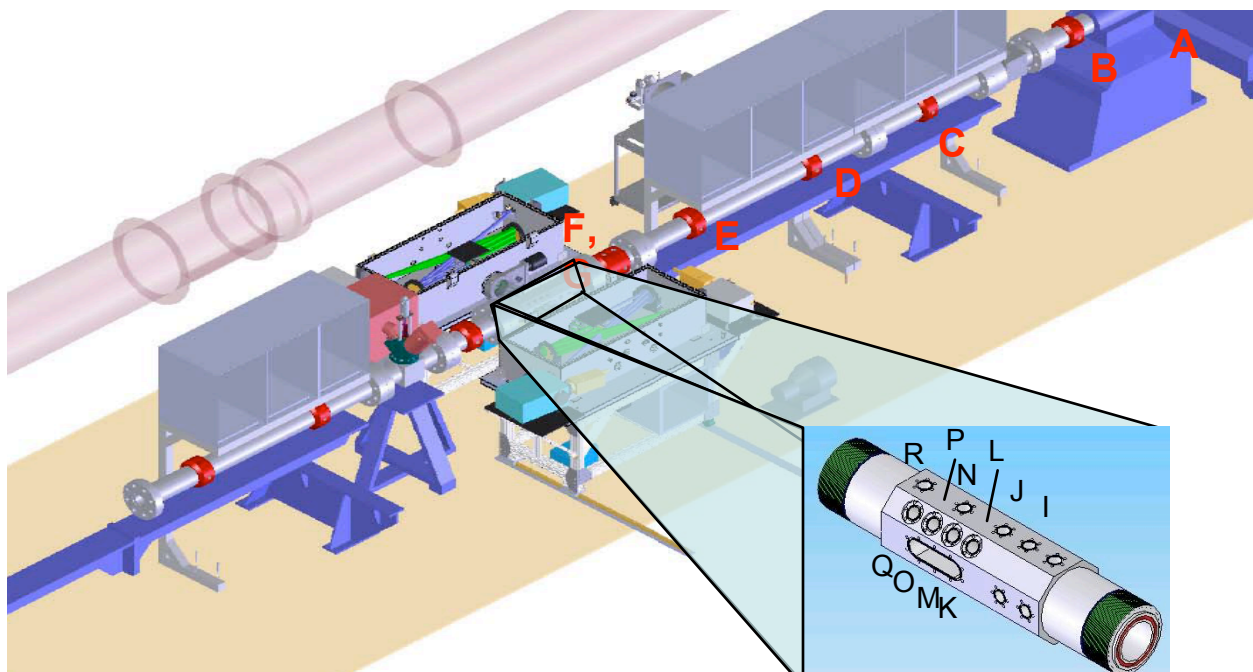


Figure 48. EAST Facility Driven Tube and components

tube from the pumping station and a gate valve isolates the high vacuum turbo pumps from the facility manifold. Gate Valve 2 is a three position valve, with the intermediate position being used to throttle gas flow and maintain the tube in intermediate pressure range (0.1-1.0 torr). The tube pressure is measured through a port C, through a valve whose state is pneumatically tied to facility valve 2. Port C has a gauge manifold with both a high vacuum ion gauge and high accuracy capacitance manometer. All the valves on the system are controlled by the gas loading system.

The vacuum system instrumentation is comprised of various pressure gauges, gauge controllers, cabling and a LabView based Data Acquisition System for recording vacuum pumping performance. The system also has a Residual Gas Analyzer (RGA) installed on the down stream pump valve. The RGA is used to determine the vacuum quality, identify vacuum leaks and gas contaminants and verify proper test gas mixtures.

4.2.3.4.4 Heater

The heater, designed by TGM, consists of a series of silicone blankets wrapped around different portions of the tube and covered with foam insulation. The blankets all have embedded thermocouple measurements which feed back to the heater control system. The heater control system uses PID control on 8-zones to adjust power delivered to maintain the temperature set point. The temperature set point is entered manually on the front panel. The heater may be turned on/off manually, or is cycled by the PLC as part of the automated pump down procedure.

4.2.3.5 Dump Tank

The dump tank is maintained at low vacuum and is isolated from the rest of the shock tube by a diaphragm. The dump tank has its own pumping and valving system which are operated independently from the driven tube vacuum system. During facility pump down, a pressure differential of several torr in either direction across the diaphragm may cause unintentional rupture of the diaphragm. To alleviate this, a bypass line was recently installed which connects the dump tube directly to the driven tube. This bypass line is intended to be open only during initial pump down of the dump tube and driven tube. This line should be closed when moving from rough to high vacuum and is operated manually.

4.2.3.6 Nozzles

Two conical nozzles exist for the 10 cm (4 in) tube of the facility: one is 1.8 m (6 ft) in length with an area ratio of 1000; the other has an area ratio of 10.

4.2.3.7 Facility Performance

Using the different driven tubes and nozzles and varying the driver/driven gas combination, driver charge pressure, and preset capacitor bank voltages, shock velocities in the range of 3.0 to 50.0 km/s (10,000 to 164,000 ft/s) have been obtained. The following is a list of the ranges of operating conditions:

- Driver charge pressure: 1.0 to 27.2 atm (100 to 2,800 kPa)
- Driven tube initial pressure: 0.01 to 10 torr (1 to 1,300 Pa) for the 60 cm (24 in) tube; 0.1 to 760 torr (13 to 100,000 Pa) for the 10 cm (4 in) tube
- Driver gas: H_2 , He, N_2 , H_2/Ne
- Driven gas: Air, H_2 , O_2 , Ne, Kr
- Capacitor bank: 16.0 to 38.0 kV voltage; 149 to 6,126 μF

4.2.3.8 Shock Tube Instrumentation

Voltage and current waveforms are recorded during each discharge. The shock velocity is computed by recording the time of shock arrival at various locations along the length of the tube, using photomultiplier tubes and high frequency pressure transducers.

4.2.3.8.1 Photomultiplier Tube Time of Arrival Sensors

The photomultiplier tube time of arrival sensors consist of several different components, including the PMT Slit Assembly, Fiber Optic Adapter and PMT Panel.

4.2.3.8.1.1 PMT Slit Assembly

The PMT Slit Assembly consists of two 50 μm wide slits aligned perpendicular to the shock tube with a separation of 4.2". Two variations of this assembly exist for mounting on the test section and upstream sections of the shock tube.

The test section mounts sit in a collar adapter that bolts directly on to the secondary round ports. On the upstream section, it is not possible to clock the slit assembly to the window port and therefore it must be oriented manually. A set-screw on the window port is used to secure the slit holder in position.

4.2.3.8.1.2 Fiber Optic Adapter

The fiber optic adapter assembly consists of three parts. The cage rod assembly from Thorlabs inserts into the PMT Slit Assembly collar on one side, and the fiber optic mount on the other side. The fiber optic mount consists of an SMA fiber optic adapter, a collimating lens, and a mount body with 6 degree of freedom adjustment. This assembly is installed directly onto the PMT slit assembly. Prior to mounting on the PMT slit assembly, the fiber optic adapter must be aligned by attaching a fiber optic illuminator and adjusting the mount settings so that the

image produced is properly aligned to the mount. The mount can then be placed on the PMT slit assembly and then alignment checked by illuminating via fiber optic through the slit and examining the image of the slit produced. This fiber optic adapter is then installed into the observation port and attached to the PMT panel via multimode fiber optic cable.

4.2.3.8.1.3 PMT Panel

The PMT panel is designed to interface an optical signal coupled from the shock tube via fiber optic and convert it to an electric signal to be collected by the data acquisition system. The PMT panel is a custom 3U 19" rack mounted panel, each with 7 SMA style fiber optic adapters for input. Each SMA adapter has a corresponding BNC connector for output signal. The SMA fiber optic adapters bolt to the front of the panel and directly couple light to the Hamamatsu H6780-20 PMTs bolted on the back of the panel.

Three panels are available for a total of 21 channels.

4.2.3.8.2 Pressure Sensors

The pressure sensors are piezoelectric sensors designed for detection of high pressure shocks. Two types of pressure sensors are employed in the EAST facility, both manufactured by PCB electronics. Previously the PCB 113A21 style pressure sensor was used and is currently being phased out however, may still be used in the upstream ports on the shock tube and are fully compatible with the existing control units for the PCBs.

The newer style sensor is the PCB 132A35. These sensors were selected for their smaller sensor cross-section which was expected to allow for more accurate detection of shock arrival. The quoted response time of these sensors is 1 μ s, though experimental observation shows that the accuracy of detecting shock arrival is much higher than this.

4.2.3.8.3 Spectroscopy

4.2.3.8.3.1 Vacuum Box

The rectangular aluminum vacuum box contains all the imaging optics for the EAST spectroscopy implementation. The vacuum box (V-box) couples to the spectrometers through window ports for visible and IR spectrometers and through a sealed port for VUV spectrometers. This port design is such that either a window mounting plate or a vacuum monochromator may be installed on it. High vacuum levels such as $1.0\text{E-}07$ can be achieved in the V-box without bake-out.

The pumping system on the vacuum box uses a 300 l/s turbo pump mounted directly underneath the box with gate valve isolation. An oil-free mechanical pump backs

this turbo pump. A second gate valve is used on the side of the vacuum box facing toward the test section. There are also several ports on the opposite side of the box which are used as feedthroughs for optical mount motor controllers and pressure gauges. The second gate valve on the tube side accesses the v-box coupling vestibule described below. While this box may in principle be used to evacuate the vacuum monochromator, this would entail pulling a rough vacuum through a narrow optical slit which may be damaged by the flow and would be inefficient. Therefore, the vacuum monochromator is evacuated with its own small 70 l/s turbo pump, which is backed by the V-box mechanical pump. The V-box is intended to remain under vacuum at all times during facility operation and surrounding appendages are designed to interface with it in a manner that does not require disruption of vacuum.

The V-box coupling vestibule couples the vacuum box to the shock tube. It consists of a bellows adaptor which bolts directly on to the rectangular secondary port. For operational purposes, it was decided that the secondary would remain bolted to the bellows adaptor at all times. This allows for the window to remain installed in its operational position during both calibration and shot data collection. While not installed in the test section or a calibration mount, the window is held on by its keeper and the force of vacuum in the vestibule. The vestibule is evacuated through a roughing port on the gate valve that is oriented toward the vestibule. Once at rough vacuum, the gate valve may be opened to pump the vestibule to high vacuum.

At present, vacuum operation is manual. The gate valves and angle valves are pneumatically controlled and can be opened or closed using a manual switch box

The V-box frame is installed on a linear glide system that allows the entire assembly to easily be coupled to and removed from the shock tube.

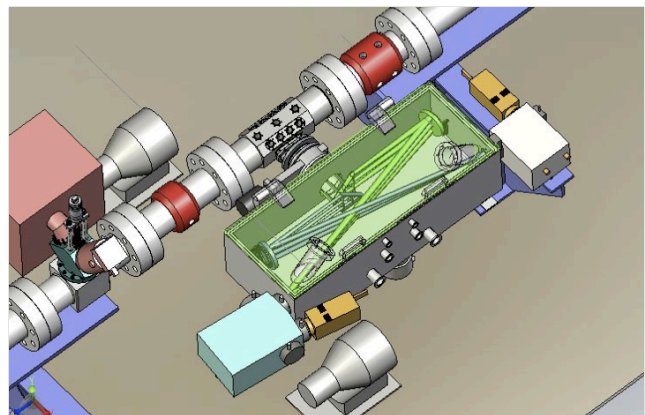


Figure 49. Vacuum Box

Two vacuum boxes are mounted on the test section, though only one box is currently operated under vacuum. The other box may be retrofitted for vacuum operation as required.

4.2.3.8.3.2 Optics

The optics design is mounted on a breadboard in each vacuum box. Each vacuum box contains two optical paths, which are each created by a series of six mirrors. The two optical paths enter the test section through the slot windows at slightly different angles, and pass through a focal point at the center axis of the tube. The first two mirrors rotate the image of the slot to a vertical orientation. The remaining mirrors direct the image and focus it onto the spectrometer slits. Each set of mirrors is chosen to optimize particular wavelength ranges depending on the spectrometer with which they are associated; thus, spectrometers may not be placed at any of the four locations arbitrarily. The mirror set associated with one camera may use an independent magnification factor.

All mirrors are mounted on high-stability optical mounts. The intent being to avoid regular adjustment of optical mounts to compensate for thermal (or other) drifts. As the v-box system requires some effort to open and adjust, frequent realignment may create significant delays in facility turnaround time. Mount stability is paramount and therefore the system must remain under vacuum at all times. The final mirror in the optical path is mounted on a motorized mount (Newport). Motor control cables are fed through vacuum sealed 15-pin feedthroughs so the mirror position may be adjusted while the system is under vacuum. The motor control switchbox (for knob selection) and joystick for position adjustment are mounted on the breadboard directly outside the vacuum box.

4.2.3.8.3.3 Spectrometers

The four spectrometers employed are from PI-Acton and include three 0.3 m spectrometers (2 x 2300i, 1 x SP300i) and one 0.4 m vacuum spectrometer (VM504). The spectrometers are equipped with three gratings each as summarized in the table 7.

Spectrometers are wavelength calibrated in WinSpec using the Spectrometer->Calibrate function. More information on the process may be found in PI-Acton application notes. This calibration needs to be performed whenever the camera is adjusted relative to the spectrometer. If the camera remains stably positioned, this calibration should be used for testing, but may be checked by taking a calibration spectrum at a stable position with a pen lamp.

Operation of the spectrometers is to be performed using VBScript macros executable in WinSpec. These macros automatically configure the cameras to desired settings

and solicit user input for settings that might change under different run conditions. These macros also automate the calibration process and apply calibration factors against the data so that data is obtained in absolute radiance units.

4.2.3.8.3.4 Cameras

Four CCD cameras are employed, one per spectrometer as detailed above. The cameras are all from PI-Acton and compatible with WinSpec software. In addition, an IR camera from FLIR (Phoenix) is available for usage if needed. The InGaAs camera does not cover wavelengths below 900 nm as the FLIR camera does. This range is covered by the PI-MAX ICCD camera. Three of the four cameras are intensified CCD arrays which are capable of making high intensity measurements at short sub-micro-second (μ s) exposure times. These arrays are optimized for different ranges of the spectrum and are associated with the spectrometers corresponding to these ranges.

The InGaAs camera uses liquid nitrogen cooling to reduce dark noise, which may completely overwhelm the signal in the IR region, where thermal excitation of electrons at room temperature is comparable to or larger than the photo-excited electrons being measured. This requires the camera dewar to be filled with liquid nitrogen approximately 30 min. in advance of usage to allow temperature, and thus dark noise, stabilization. The InGaAs camera is

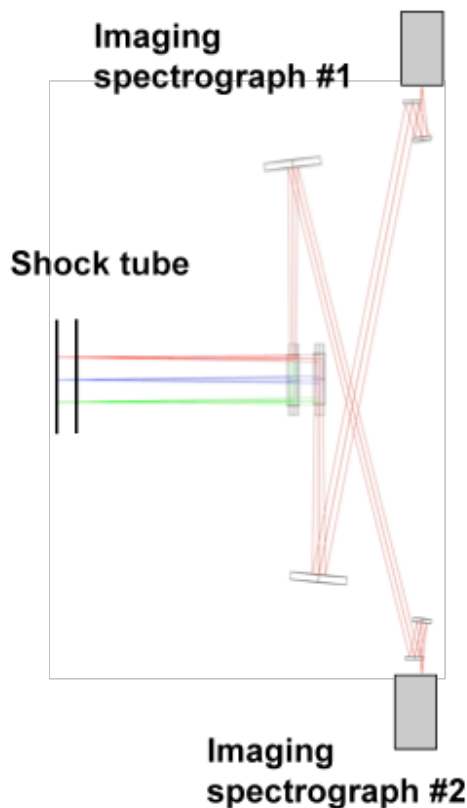


Figure 50. Optical paths in Vacuum Box

Table 7. Spectrometers in use at EAST Facility

Spectrometer	Position	Camera	Lo-Res Grating		Lo/Md Res Grating		Hi-Res Grating	
			Blaze/ Range	Ruling (g/mm)	Blaze/ Range	Ruling (g/mm)	Blaze/ Range	Ruling (g/mm)
VUV (VM504)	SE	1024x1024 ICCD	300 nm 200-450	150	150 nm 120-300	600	150 nm 120-300	2400
UV/VIS (SP2300i)	NE	512x1024 ICCD	300 nm 200-450	150	HVIS 200-450	1200	HUV 185-375	3600
VIS/NIR (SP300i)	NW	512x512 ICCD	500 nm 335-750	150	750 nm 500-900	1200	HVIS 300-800	2400
IR (SP2300i)	SW	256x312 InGaAs	800 nm 535-1200	150	1250 nm 830-1900	150	1250 nm 830-1900	600

not intensified and has a minimum exposure time of 1 μ s. At present, it is not known whether the sensitivity of the InGaAs camera is linearly proportional to exposure time; the FLIR camera was not. This means that absolute radiance calibration may require additional correction if the exposure time must be adjusted.

4.2.3.8.4 Calibration Sources

Two calibration sources are employed: an integrating sphere for wavelengths > 300 nm and a Deuterium lamp for wavelengths < 300 nm. Both calibration sources have a coupling piece designed to allow attachment to the vacuum box through the secondary slot window holder.

4.2.3.8.4.1 Integrating Sphere

The integrating sphere is a 12" diameter sphere with 4" exit port providing a calibrated absolute radiance output. The integrating sphere uses 5 individual lamp sources, including 4 Quartz-Tungsten Halogen (QTH) lamps and a Xenon arc lamp. The xenon arc lamp is UV filtered to prevent excess energy deposition into the integrating sphere. As the lamps provide approximately 1.2 kW of power, the integrating sphere becomes very hot and requires external cooling by way of an N₂ purge line with a flow interlock which protects the highest power QTH lamp. Other lamps may be used without the N₂ flow on, but if the flow deviates from its set point, the high power lamp will be locked out.

Calibration data for the integrating sphere is provided by the manufacturer at various settings. The integrating sphere is also equipped with a fiber-optic coupled spectrometer with sensitivity from 300-900 nm and a germanium photodiode with sensitivity in the IR. These detector sources are deemed to be more reliable radiance standards than the manufacturer provided radiance curves due to possible drifts in the lamps. Nevertheless, the QTH lamps should be operated using current (not voltage) settings that match the manufacturer's calibration conditions (4.490 A on ITHS-600 and 6.250 A on the other three lamp power supplies).

The spectrometer, from Ocean Optics, uses SMS software to monitor the integrating sphere absolute radiance. This data may be saved in the form of a .scn file which is used as the calibration standard by the Matlab CCDResponse function. If the range of interest is outside of that detected by the spectrometer, the photodiode current, displayed on the Keithley picoammeter should be recorded and used to normalize the calibration data against the reference data. This function is performed entirely within the software.

4.2.3.8.4.2 Deuterium (D2) Lamp

The D2 lamp is an arc source with absolute radiance calibration standard and vacuum spectrometer mounting configuration. In order to obtain the D2 lamp spectrum over the spatial dimension of the imaging spectrometer, a translating stage was constructed for the D2 lamp. The D2 lamp is mounted directly onto the translating stage, which in turn couples to the V-box. The region between the translation stage and window is equipped with a purge port to remove oxygen from the calibration path. A flow of argon or nitrogen is controlled from the rotameter panel. Approximately 15 min. of purging should be performed to remove the oxygen and effectiveness of the



Figure 51. Integrating Sphere

purge may be verified by collecting spectra in the VUV and identifying the elimination of absorbance at 140 nm.

The translation stage is attached to EZII motorized linear stage from Oriental Motors. The motor settings may be programmed via EZED2 software. Once programmed, the settings are stored within the motor and it may be operated without computer interface.

4.2.3.9 Support Systems

4.2.3.9.1 Control Systems

The EAST has multiple control systems that operate both current and legacy equipment. The legacy equipment, including the West (60cm) tube and cold driver systems, are largely disconnected though parts of these control systems are still in place and in some cases include interlocks to equipment that is still used. Complete demolition of these systems may be attempted sometime in the future. The control systems that are presently in use are the firing control system and the new gas loading system.

4.2.3.9.1.1 Fire Control

The firing control system dates back to the initial construction of the facility and controls the capacitor bank charge and discharge with multiple safety interlocks. Complete understanding of this system would require reference back to older historical documents and wiring diagrams. This document details only some of the relevant changes made in 2007-2008.

When the fire sequence is initiated, the capacitor bank charges up at a rate of 500 V/sec. The digital gauge operates as a simple on/off controller that ends the charging process once the programmed set point is obtained. This allows the set point to be set deterministically with accuracy on the order of 10 V.

The fire control system is interlocked to prevent access to the shock tube during charging and firing. The fire control system has also been integrated with the gas loading system, described below. When firing sequence is engaged the gas loading sequence is initiated. If the gas loading sequence does not conclude after 1 minute, the fire sequence is halted by tripping the 86 breaker. The firing sequence includes multiple time delay relays which must be set to make the fire sequence longer than the time programmed into the gas loading sequence.

4.2.3.9.1.2 Gas Loading Control

The gas loading control system involves several components, many of which are depicted in the P&ID above. Gas flow is controlled by MKS mass flow controllers (MFCs). The MFCs are in turn controlled via the MKS 250E pressure control system. The MKS 250E adjusts the flow rate on the MFCs in order to maintain a pressure

set point within the shock tube. The MKS 250E may be operated manually by front panel control or automatically by a programmable logic controller (PLC). The set points on the individual MFC channels determine what the maximum flow rate can be during the gas fill process. Successful operation of the 250E also requires the gas loading valve to be open and the shock tube gate valve 2 set to intermediate position.

The PLC controls all aspects of the gas loading system as well as the facility vacuum system. Interface to the PLC is possible via Proficy software to diagnose errors or edit the PLC program, though routine operation of the PLC is performed via the gas loading panel installed on the racks above the shock tube. The gas loading panel may be switched between manual and automatic mode. In manual mode, the gas loading panel allows for manual operation of 5 pneumatic valves – two facility valves, two gate valves and the gas loading valve. In automatic mode, these valves are controlled according to preset sequences, along with the tube heater and gas loading system.

The pre-programmed sequences of the Gas Loading system are meant to perform two primary functions: overnight shock tube evacuation and purging and test gas gas loading. The evacuation function cycles through 5 stages, denoted as: Evacuate/Heat, Heat/Purge, Evacuate/Heat, Heat/Purge, Evacuate, each of which last approximately two hours. Purge processes use the gas loading function, maintaining the pressure set point on the MKS250E, while the heat processes maintain the heater at the set points on the heater controller. If an error occurs during this process, the system fault light is illuminated and the system is placed in 'Evacuate' mode (i.e. pumping valves open). If the fault is related to an inability to maintain vacuum in the system, all valves will be closed and the system will be left in 'Quiescent' mode. If an operator is present during the pumpdown sequence, the stages may be cycled through using the Next Stage/Previous stage buttons. A 5-second delay occurs before actuating valves so the operator may skip over stages without actually entering them.

4.2.3.9.2 High Voltage System Measurements

The high voltage (HV) system includes the capacitor bank, HV Transformer, HV switches, cabling and associated measurement systems. The high voltage system is controlled by the firing control system. Measurement of voltage on the capacitor bank is obtained by connection to a resistive voltage divider. The signal on the voltage divider reads 114 mV per kV on the capacitor bank. Measurement of current is performed by use of a voltage divider on the ground line between the capacitor bank and arc driver. Both the Voltage and Current signals are run to the data acquisition system.

4.2.3.9.3 Instrument Rack

A series of new instrument rack was installed in the EAST facility directly over the shock tube. These racks were installed on a cantilevered structure so as not to restrict access on the east side of the tube. Minimal interference is introduced on the west side by these structures. Three structures with three 19" racks each were installed, two over the upstream section and one over the downstream section. All electronics, controls and computers for operation of the facility are installed in these racks, excepting the firing control in the control room and controls for the V-boxes and spectroscopy equipment which are mounted under the V-box support tables.

There is 80U of space available for additional instrumentation outside of the permanently installed facility related systems.

4.2.3.9.4 Gas Delivery

4.2.3.9.4.1 Gas Rack

The Gas Rack was installed adjacent to the driver and allows permanent placement of the test gas next to the loading valve. The gas rack is designed to accommodate three full sized cylinders and two half-sized cylinders. The panel above the gas rack contains regulators for the gases, the mass flow controllers and a manifold for mixing prior to introduction into the test section. The regulators are mounted on the panel with pigtail connections to the cylinders for ease of change out. The test gas regulator has a three way valve which allow the test gas to be changed between two cylinders (presently Air and Mars gas mixture) without disconnecting any systems. Upstream of each regulator is installed a 0.013" diameter orifice as part of a M-M NPT connector. Downstream of each regulator are pressure relief valves with adjustable discharge pressure from 50-150 psi. In the event of a regulator failure, these valves will discharge the gas and prevent damage to the MFCs from overpressure. The upstream orifice limits the maximum flow rate through the regulator so that the pressure relief valves may discharge gas without additional pressure buildup beyond their cracking limit.

4.2.3.9.4.2 Compressed Air

The compressed air system is used to control all pneumatic valves on the shock tube and vacuum boxes. Tubing connected to the compressed air source is blue in color. At present the compressed air source comes from another building and we have no control over its availability. In the future a dedicated air compressor will be installed for the facility.

4.2.3.9.4.3 Purge Gas System

The purge gases refer to gases plumbed to three rotameters near the downstream end of the test section. These gases are used to convectively cool the integrating sphere, purge the VUV camera of moisture and oxygen and to purge the deuterium lamp calibration mount. The first two sources are connected to a nitrogen source via green tubing while the final one may be connected to either nitrogen or argon. Due to the potential large quantities of nitrogen used for purging, the nitrogen is connected to the gas boil off outlet of a liquid nitrogen dewar at the west wall of the facility. This provides a longer lasting source of pure N₂ gas than a gas cylinder can. This dewar is also used to provide liquid nitrogen for cooling the InGaAs detector.

Two of the rotameters have laser based flow sensor interlocks. The laser sensor on the right side of each rotameter detects the presence of the rotameter flow ball and enables the interlock when the ball intersects the laser. In other words, the interlock is on when the flow rate matches the position of this sensor. The left sensor is not used. Deviation from this set point on either the high or low side will trip the interlock. The interlock corresponding to the integrating sphere is set near 40 sccm and controls the 600W QTH lamp. The interlock for the VUV camera is set at 5 sccm and is connected to a time delay relay which requires the purge to run for 30 min. before power is provided to the camera. The rotameter for the D2 lamp purge is not interlocked.

4.2.3.9.5 Data Acquisition System

The data acquisition system is housed within a VXI crate from Spectral Dynamics. Within the crate are several card slots. Presently the first 5 slots are occupied by ZT412 high speed oscilloscopes from ZTEC instruments and the next 3 slots are occupied VX2805 Data Acquisition Modules by Spectral Dynamics. The ZT412s operate 4 channels each at up to 400 MS/s. The VX2805 have 8 channels each at 5MS/s. Both cards use 16-bit digitization and are controlled by IMPAX software from Spectral Dynamics. Channels on the ZT412 are directly connected via coaxial connectors. The VX2805s use two 9-pin connectors for data acquisition. The cables for these are connected directly to coaxial patch panels directly beneath the VXI crate. The BNC inputs on each patch panel are labeled 1-8 corresponding to the 8 channels on each card. The panels from top to bottom correspond to cards from left to right within the crate.

In the IMPAX-SD software, channels are numbered sequentially from 1-36, with no obvious distinction between the cards responsible for each channel. Channel numbers therefore are read on the cards from left to right, so that

channels 1-4 originate from the first ZT412 card, 5-8 from the second, and so on. The first VX2805 card therefore operates channels 21-28. The first ZT412 card serves as a master to the remaining ZT412 cards, while the first VX2805 card is the master to the second VX2805. The system trigger is configured via the first ZT412 Trig In input. The ZT412 in turn sends trigger signals via ECL0 and TTL1 on the backplane, which are used to trigger the slaved ZT412s and the VX2805, respectively. A slight mismatch on the order of 10 ns is observable between the slaved ZT412s and is attributed to trigger signal propagation time. The ZT412 trigger in may be set as an edge or level signal at any value between -1 to 1 V. The current input, which is logged on the low speed cards, is also wired to the trigger input. Because of the low range of voltages allowed on Trig In, a 10x coax attenuator is installed on this coaxial line, and the card is set to trigger when this signal reaches 0.13 V. This trigger level is chosen for similarity to the old master signal source signal, which was based on a voltage level of 13V in the absence of attenuator or additional voltage dividers. The trigger signal does require a low-pass filter to remove high frequency noise originating from the closure of relays in cap bank control circuit. A coaxial line filter with 1 MHz cutoff is employed for this purpose. The arc current is observed to have a ringing on the order of 100 kHz so is not affected by this filter.

The voltage signal from the cap bank is also recorded on the data acquisition system. Contrary to the other signals, the voltage signal is a slowly varying signal, accumulating over the course of several seconds prior to the shot. This requires a time base that is vastly difference from that of the digitizers and would not be possible to record with use of a special feature in IMPAX-SD known as "Real Time Monitor". The Real Time Monitor collects and averages data from the VX2805 channels on a continuous basis and exports it to a log file. This function may run continuously until the cards are triggered. Therefore, to record the voltage profile along with other data, the Real Time Monitor must be started first, being set to record only the voltage signal and no others. The entire system is then armed while real time monitor is running via the Run->Manual command prior to the shot. At completion of the shot, individual channel data is stored in files of the format 0nn0nn.001, where nn is the channel number, while the real time monitor data is stored in a .log file specified by the operator. These files may

then be loaded into Matlab and processed automatically using the ProcessDAS routine to produce a single file of compiled data.

Operation of the IMPAX-SD software is non-intuitive and settings should be made by individuals well trained in the operation of the program. A usage manual prepared in-house is available which is more useful for learning its operation than the IMPAX manual. In general, it is recommended to load the existing experiment as a template for new runs rather than attempting to configure all settings from scratch. Within a single test series, shot data should be collected using a single configuration file rather than creating new configuration files for each shot.

4.2.3.9.6 Laboratory Network

The EAST facility uses 8 computers in its operation. This includes 4 spectrometer computers (one per spectrometer/camera), an integrating sphere control computer, data acquisition system control computer, vacuum data acquisition system (VDAS) computer and a license/software server. The VDAS computer also controls the residual gas analyzer and interfaces with the PLC. These computers are all connected on a single private laboratory network which does not interface to any other internal or external network. The computers are connected by a single router. Also interfaced on the router are the PLC and two COM over IP units that interface the SRS controllers, RGA and weather station. All computers have a network-shared Z: drive which enables file interchange over the network. Furthermore, a RAID array backup system on the network automatically pulls and archives files from the computers nightly.

Six of these computers, including server, integrating sphere and spectrometer computers, are connected to a two-user KVM switch. The KVM switch feeds mouse, keyboard and monitor connectivity to these computers to one of two mobile terminal carts on opposite sides of the tube. Any one of these computers may be accessed from the cart by pressing PrntScrn. In addition, the four spectrometer computers each have a 'local' KVM connection over Cat5 cable that allows the spectrometers to be controlled from dedicated stations in the control room. The two data acquisition computers share a single KVM switch with terminals located both in the control room and on a stationary table in the facility. These terminals use the same KVM switch so that they simultaneously access the same computer.

4.2.3.6 Bibliography

The following papers describe the EAST Facility and some research programs performed in it at the Ames Research Center. The list is not exhaustive.

- Sharma, S.P. and Park, C.: Operating Characteristics of a 60- and 10-cm Electric Arc-Driven Shock Tube -- Part I: The Driver. *J. Thermophysics*, July 1990, pp. 259-265.
- Sharma, S.P. and Park, C.: Operating Characteristics of a 60- and 10-cm Electric Arc-Driven Shock Tube -- Part II: The Driven Section. *J. Thermophysics*, July 1990, pp. 266-272.
- Loubsky, W.J. and Reller, J.O.: Analysis of Tailored Interface Operation of Shock Tubes with Helium-Driven Planetary Gases. *NASA TN D-3495*, July 1966.
- Dannenber, R.E. and Humphry, D.E.: Microsecond Response System for Measuring Shock Arrival by Changes in Stream Electrical Impedance in a Shock Tube. *Sci. Inst.*, Nov. 1968, pp. 1692-1696.
- Seegmiller, H.L. and Mazer, L.: A 500,000 Sample Per Second Digital Recorder for the Ames Electric Arc Shock Tunnel. *ICIASF 1969 Record*, pp. 243-247.
- Dannenber, R.E. and Silva, A.F.: Exploding Wire Initiation and Electrical Operation of a 40-kV System for Arc-Heated Drivers up to 10 Feet Long. *NASA TN D-5126*, April 1969.
- Dannenber, R.E. and Katzman, H.: An Application of Optical Telemetry to Shock Tube Measurements. *Rev. Sci. Instr.*, May 1969, pp. 640-642.
- Dannenber, R.E.; Cheng, D.Y.; and Stephens, W.E.: A Novel Use of a Telescope to Photograph Metal Diaphragm Openings. *AIAA Journal*, June 1969, pp. 1209-1211.
- Reddy, N.M.: Shock-Tube Flow Analysis with a Dimensionless Velocity Number. *NASA Tn D-5518*, Nov. 1969.
- Dannenber, R.E.: An Imploding Trigger Technique for Improved Operation of Electric Arc Drivers. *Shock Tubes, Proceedings Seventh International Shock Tube Symposium*, Edited by I.I. Glass, University of Toronto Press, Toronto, Canada 1970, pp. 186-200.
- McKenzie, R.L.: 5- μ m Laser Radiation from a Carbon Monoxide Gasdynamic Expansion. *NASA TM 62,006*, Oct. 1970.
- Dannenber, R.E. and Cheng, D.Y.: Dark-Pause Measurements in a High-Pressure Arc Discharge. *AIAA Journal*, Jan. 1971, pp. 184-186.
- Humphry, D.E. and Dannenberg, R.E.: Electrical Instrument Measures Position and Velocity of Shock Waves. *NASA Tech. Brief 71-10143*, May 1971.
- Reller, J.O. and Reddy, N.M.: Analysis of the Flow in a 1-MJ Electric-Arc Shock Tunnel. *NASA TN D-6865*, June 1972.
- Dannenber, R.E. and Silva, A.F.: Arc Driver Operation for Either Efficient Energy Transfer or High-Current Generation. *NASA TM X-62*, 162, May 1972.
- Dannenber, R.E.: A Conical Arc Driver for High-Energy Test Facilities. *AIAA Journal*, Dec. 1972, pp. 1692-4.
- Reller, J.O.: Design and Performance of the Ames Electric-Arc Shock Tunnel. *NASA TM X-2814*, June 1973.
- Dannenber, R.E. and Slapnicar, P.I.: Dynamic Discharge Arc Driver. *AIAA Paper 750176* presented at the 13th Aerospace Sciences Meeting, Pasadena, Cal., Jan. 1995.
- Dannenber, R.E. and Slapnicar, P.I.: Computer Modeling of Arc Drivers. *NASA Tech. Brief B75-10130*, June 1975.
- Schneider, K.P. and Park, C.: Shock Tube Study of Ionization Rates of NaCl Contaminated Argon. *Physics of Fluids*, August 1975, pp. 969-981.
- Borgardt, F.G. and Kaplan, D.E.: C3 Plasma Conductivity Studies. *LMSC-D501830*, March 1976.
- Jaffe, N.A.: Experimental Investigation of the Interaction Between Strong Shock Waves and Water Droplets. *DNA Report 401SF*, July 1976.
- Dannenber, R.E. and Slapnicar, P.I.: Development of Dynamic Discharge Arc Driver with Computer-Aided Circuit Simulation. *AIAA Journal*, Sept. 1976, pp. 1183-8.
- Slapnicar, P.I.: Computer Aided Nonlinear Electrical Networks Analysis. *NASA CR-2810*, March 1977.
- Dannenber, R.E.: A New Look at Performance Capabilities of Arc Driven Shock Tubes. *Proceedings of the Eleventh International Symposium on Shock Tubes and Waves*. Edited by B. Ahlborn, A. Hertzberg, and D. Russel, Univ. of Washington Press, 1978, pp. 416-43.
- Tate, E. and Zauderer, B.: MHD Generator Investigations -- Annual Report, Oct. 1976 to Dec. 1977, General Electric Company, 1978.
- Dannenber, R.E.: "GAIM" -- An Advanced Arc-Driver Concept. *Nonideal Plasma Workshop*, ONR, Pasadena, Cal., Nov. 1978.

Craig, J.A.: Shock Attenuation Measurements in a Model of the MX Trench -- Data Presentation. Science Applications Inc., SAI-780-620-LA, Dec. 1977.

Dannenberg, R.E. and Milton, B.E.: Optimized Performance of Arc Heated Shock Tubes. Proceedings 14th International Symposium on Shock Tubes and Waves, Edited by R. Archer and B. Milton, Sydney Shock Tube Symposium Publishers, New South Wales, Australia, 1984, pp. 110-117.

5.0 Operating and Safety Procedures

5.1 Use of the Operating and Safety Manual

There are manuals for each of the facilities which cover the operation of the Facility and note safety procedures and regulations. Copies of these manuals are kept in the offices of the respective Facility Manager. Every building at ARC also has a Building Emergency Action Plan (BEAP) that identifies hazards and evacuation procedures. Experimenters and temporary personnel working on or utilizing the Facilities should become familiar with safety rules and emergency procedures noted within these manuals. A summary of this information is given in Section 7.0 Emergency Procedures.

5.2 Emergency Aid and Information

Resident personnel working after normal business hours must notify the Ames Duty Office at extension 4-5416. Additionally, personnel must advise the Duty Office when departing for the night. Should an emergency arise in the Facility, response teams will be aware of your presence. Also, for safety and security reasons, keep exterior building doors secured after entering or exiting the building.

To request emergency services, as for fire or ambulance, call the Ames emergency number—911 from a Center phone, or (650) 604-5555 from a cell phone.

6.0 Primary Hazards and Safety Features

Primary hazards which exist in the Thermophysics Facilities are high voltages, high-pressure gases and water, vacuum chambers, explosives, flammable gases, non-breathable gases, and personnel entrapment. These hazards are examined in the following paragraphs.

The facilities are located adjacent to active machine shop areas. As such, it is not allowed for personnel (including investigators) working in the facility buildings to wear open-toed shoes nor short pants. It is strongly recommended that these personnel wear steel-toe safety shoes; hearing and eye protection are required during facility operations.

6.1 High Voltage

6.1.1 Arc Jet Complex

The high voltage on the arc heater is rendered safe by placing the unit behind a barrier which removes the possibility of contact with personnel. Continual vigilance is required to ensure that no electrical conductor be allowed to violate the barrier either in the regions of the arc heater or the test chamber. After personnel are evacuated from within the arc heater barrier enclosure and the test section, a key interlock system ensures that the barriers are in place and the test section is closed before the power

supply can be energized. The hazard of arc-over from the high-voltage components is minimized by the heater design, which utilizes only non-conducting materials in the vicinity of the arc heater, and by maintenance of insulation integrity between heater components. Only qualified personnel are allowed to contact the arc heaters and all supporting power distribution equipment.

6.1.2 Range Complex

In the Range complex, high voltage devices which can be potentially hazardous include capacitor banks (40 kV), spark gaps (7,000 volts), kerr-cells (24,000 volts) and their respective power supplies. All of the high voltage components (i.e. capacitors) are well-sealed and contained within grounded enclosures. Similarly all of the cables and connectors are grounded and insulated. Under routine operating conditions, these devices are only energized just prior to a test when no personnel are present. Thus the most likely hazard to arise with any of these items is when they are being serviced. Only electricians and experienced facility staff members, using appropriate electrical test equipment, are allowed to service these devices.

6.2 High-Pressure Gases and Water

High-pressure gases in standard steel bottles are used in all of the Thermophysics Facilities. These bottles are restrained to prevent falling in the event of seismic activity. Furthermore, these bottles are always used with regulated output. All storage and delivery systems are subject to standard guidelines for high pressure component design and maintenance as outlined in the Ames Health and Safety Manual.

High-pressure gases and water in the arc heaters are rendered safe by placing the units behind the arc heater barrier. The high-pressure-gas systems are provided with relief valves and rupture disks.

6.3 Vacuum Chambers/Non-breathable Gases

6.3.1 Arc Jet Complex

The vacuum enclosures in the Arc Jet Complex include the test sections and diffusers during facility operation. These elements are designed to contain the pressure difference of one atmosphere, however, since the test stream is very energetic, constant vigilance must be maintained to avoid overheating of these elements which could reduce their material strength. Plexiglass covers are maintained in place over the large side windows to provide shielding in the event of window breakage. Entry into the test chambers by persons other than Branch personnel is restricted except under close supervision. Entry into the SVS is only via strict procedures for confined space entry outlined in the Ames Health and Safety Manual.

Test chambers and enclosures are plumbed to non-breathable gas storage cylinders (e.g. argon and nitrogen). Entry is restricted to Branch operations personnel except under close supervision. Because hazards due to asphyxiation and toxicity can exist inside closed spaces, adequate ventilation must be established prior to entry. Leakage of non-breathable gases into basements, enclosures, or trenches could cause asphyxiation. Therefore, oxygen deficiency detectors are mounted in various locations in N234 and N238 which will alarm before these dangerous conditions can build up. The exception is the walk-in test chambers where such oxygen sensors can not function after exposure to vacuum. Careful entry practices must be observed.

6.3.2 Range Complex

Each facility in the HFFF has a vacuum chamber which consists of a sabot separation tank, test section, and impact chamber. Each of the vacuum chambers is considered to be a "confined space" because of egress restrictions. For routine operating conditions none of the chambers requires an entry permit. However, for specialized experiments that use test section environments other than air, it may be necessary to develop special entry procedures. These procedures might include such things as extended purging periods and/or use of oxygen deficiency meters. Special entry procedures must be approved by both the Center's safety office and ASF branch management during the test readiness review process.

The HFFAF test section contains 72 glass windows ranging in size from 12 to 15 in (30 to 38 cm) in diameter. These windows are inspected frequently to prevent implosive fracture. Located on top of the sabot separation tank is a 48 in (120 cm) diameter blow-off diaphragm to prevent over-pressurization of this segment of the facility. Prior to evacuating the test section and dump tank, the entire facility (gun, test section, and shock tube rooms) is secured, doors locked, and "Testing in Progress" signs posted. All personnel that are not directly involved with the test must either remain in the control room, or leave the facility entirely. Furthermore, personnel who must enter the test section room, while this portion of the facility is evacuated, are instructed to remain behind the film boxes. This is to minimize possible injury should a window fail.

6.4 Explosives (Range Complex)

Smokeless powder and electrically activated detonators are used for routine testing in both the Ballistic Range Complex and the AVGR facility. Powder charges are assembled within a specially equipped "powder preparation rooms." The floors of these rooms are covered with conductive sheeting. This combined with the complete

grounding of all benches and cabinets effectively prevents the buildup of static electricity. Personnel use wrist grounding straps whenever they perform tasks within the room. Wrist strap integrity (conductivity) is checked prior to entering the powder preparation room. Furthermore, full face safety shields are utilized whenever handling explosive charges and all electrically actuated devices are shorted and grounded until their actual installation. As a general rule, only those supplies (powder and detonators) required for one week of testing are stored in the powder preparation rooms, all remaining supplies are retained in the Air National Guard explosives bunker.

6.5 Flammable Gases

Hydrogen in standard 2000 psi (13.8 MPa) steel bottles, is routinely used as the propellant gas in light-gas guns. The hazards associated with having this flammable gas within the Ballistic Range Complex and the AVGR facilities are minimized by only hooking up one hydrogen cylinder per gas loading cart, and by having high-flow supply and exhaust fans operating whenever a supply valve is opened. In addition, no personnel are present (in the gun room) when the guns are actually loaded.

6.6 Personnel Entrapment

6.6.1 Arc Jet Complex

Personnel entrapment in the test section and subsequent evacuation of the test section is a potentially lethal hazard. This is prevented by thorough inspection by the facility operator required in the operating procedure, and the interlock system. If both of these should fail, an emergency push-button is available to anyone inside of the test section which will sound an alarm, give indication on the annunciator, close the vacuum isolation valve, and prevent the electrical power from being applied. Entry into the SVS for maintenance is strictly controlled via confined space entry procedures outlined in the Ames Health and Safety Manual.

6.6.2 Range Complex

In the Range Complex, the Firing Officer assigned to each test is personally responsible for inspecting the interior of the test section and sabot separation tank prior to locking the access doors. All facility personnel are instructed to lock the door in the open position and flip down the "Man in tank" sign upon entering the dump tank and test section. This sign alerts the firing officer that someone is within the vacuum chamber, and prevents the access door from shutting and sealing completely. Furthermore, the operating procedures requires several facility checks, to make certain that all personnel are accounted for and that no one remains in the facility.

7.0 Emergency Procedures

Emergency procedures to be followed in the case of a facility failure are outlined in the respective facility and building safety manual. The facility operators are trained to deal appropriately with these emergencies; in the case of any accident causing injury or property damage, the following procedures will be followed.

7.1 Direct Response Action

Immediately following an accident, any qualified person on the scene will take the following actions until relieved by competent authority:

1. provide assistance to injured persons;
2. take action to limit or prevent further injuries or damage;
3. call the Emergency Control Center, 911, giving necessary information on the nature of the accident, the type of assistance needed, and the location of the accident;
4. notify the Facility Manager and the Branch Chief;
5. secure the identity of witnesses; and
6. secure the area to prevent actions that could hamper or prevent investigation of the accident

7.2 Fire Alarm

The operation of this alarm is initiated by smoke and heat sensors located in the building and is a signal to evacuate the building and stand by outside to direct emergency personnel to the source of the trouble. In all cases of fire, even when it is controlled by facility personnel with fire extinguishers, the fire department shall be called. One person shall be directed to stand outside the building to direct emergency personnel to the source of the trouble. This is important because of the possible danger of a secondary flareup of the fire. The Principal Investigator and/or his/her staff may be called upon for this duty.

In order to function quickly in the case of an emergency, the Principal Investigator and his/her staff should learn the location of fire extinguishers and of all exits from the building, as described in the BEAP